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LOW GRADE HEAT RECOVERY

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LOW GRADE HEAT RECOVERY

Abstract
The purpose of this design project is to evaluate the feasibility of power recovery from a low-grade heat source. Specifically, the design team investigated the technical and economic issues associated with building a plant to recover power from a waste heat stream that is the byproduct of another process, such as a power or chemical plant. The project specifies that the incoming hot air stream is at 120psi and 230oF, and there are no external heat sources. The project champion suggests the design team to use a modified organic Rankine cycle with a dense liquid expander for more thermodynamically efficient heat recovery.

However, the design used in this report presents a modification on the suggested cycle by adding a flash evaporator to separate a liquid-vapor stream before the condenser. This change decreases costs associated with the size of the condenser, as well as the amount of cooling water needed. This provides for a more economical and efficient process.

Concerning the process thermodynamics and readiness, we conclude that the low-grade heat recovery cycle is feasible in its current iteration, and it provides a viable method to recover energy from a low-grade heat stream. From an economic standpoint, we conclude that this process would be economically feasible if energy costs increased by 15%-20%, to about $0.096/kWh. However, it is not currently economically competitive, because the cost of the equipment and building the plant to recover the energy are significantly high in comparison to the amount of energy recovered from the process.

Disciplines
Heat Transfer, Combustion
Low-Grade Heat Recovery
Considerations on the limits of power generation using a modified Organic Rankine Cycle with a dense fluid expander

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Edward Nie
Ali Raza
Brian Wright

Industrial Consultant:
Mr. Adam Brostow

Faculty Advisor:
Dr. Wen K. Shieh

April 13, 2010
Department of Chemical Engineering
University of Pennsylvania
Dear Professor Fabiano and Dr. Shieh,

The following report consists of our solution to the senior design project, *Low-Grade Heat Recovery*, as proposed by Mr. Adam Brostow.

This report details the process equipment required and the profitability analysis for the project. With a heat source of 65,000 lb-mol/hr air at 230°F and 120 psia and a power input requirement of 411 kilowatts, the process produces 1.8 megawatts of net power. The process could be currently implemented because all process components are readily available on the market.

At a price of $0.08 per kW-hr, the process yields a net present value of -$1.857MM and an internal rate of return of 2.32%. Using sensitivity analysis and cost estimation, the required price of electricity would be $0.096 per kW-hr to give a positive net present value and an IRR of 6.28%. Other external factors aside from financial aspects are also addressed in this report. For example, the positive externality of the ability to produce additional electricity with no additional polluting emissions.

However, our conclusion is that although the process is thermodynamically feasible, at the current prices of electricity and the capital costs for the equipment, the process is not economically feasible.

Sincerely,

_________________________________________  ______________________________________
Luisa Herrmann-Rodrigues                      Edward Jing Nie

_________________________________________  ______________________________________
Ali Hasan Raza                                  Brian Michael Wright
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Abstract

The purpose of this design project is to evaluate the feasibility of power recovery from a low-grade heat source. Specifically, the design team investigated the technical and economic issues associated with building a plant to recover power from a waste heat stream that is the byproduct of another process, such as a power or chemical plant. The project specifies that the incoming hot air stream is at 120psi and 230°F, and there are no external heat sources. The project champion suggests the design team to use a modified organic Rankine cycle with a dense liquid expander for more thermodynamically efficient heat recovery.

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Introduction

Low-grade heat recovery entails the recovery of energy from hot fluid streams under 300°F through power generation processes. Over a series of unit operations entailing heat exchangers, turbines, condensers, separators, and pumps, thermal energy can be converted to reusable electrical energy. While the energy generated is not comparable with the amount produced at a full-scale thermal power plant, low-grade heat recovery reconsiders the possibility of extracting energy from fluid streams that would otherwise be sent directly “up the stack”.

With current environmental regulations limiting CO₂ emissions, energy recovery processes have become an important issue. Electrical generation is becoming increasingly competitive, as the wholesale price of electricity continues to decrease (Beaver, 2001). The recovery of energy from these streams is expected to save on the amount of fossil fuels burned. Considering the economics could be favorable, imposing low-grade heat recovery processes could constitute better environmental compliance. Therefore, there is an increased incentive to recover heat from relatively low-temperature sources such as hot compressor discharge, hot automobile gas, hot chemical reactor streams, geothermal springs, and other sources of renewable energy. (Beaver, 2001)

This project explores various models for recovering the available duty of a hot process stream. The goal is to compare the power generated from the base case of the organic Rankine cycle to a new power generation cycle suggested by Air Products and Chemicals Inc. consultant Adam Brostow in United States Patent 7,278,264 and other team engineered designs. The project team explored a variety of refrigerants through a series of sensitivity analyses on pressure, flow rate, and temperature to maximize heat recovery. Ammonia was initially suggested as a working fluid, and refrigerants R-134a, R-245, carbon dioxide, and a variety of hydrocarbons were also explored. The project team determined ammonia to be the most suitable refrigerant and prepared the following report to meet the project charter’s requirements. The economic feasibility study of this project was also conducted and the results are included in the report.
## Project Charter

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Low Grade Heat Recovery: Considerations on the limits of power generation using a modified Organic Rankine Cycle with a dense fluid expander.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Champions</td>
<td>Air Products and Chemicals, Inc.</td>
</tr>
<tr>
<td>Project Members</td>
<td>Luisa Herrmann-Rodrigues, Edward Nie, Ali Raza, Brian Wright</td>
</tr>
</tbody>
</table>
| Project Scope | In-Scope:  
- Waste heat recovery from power plant generation.  
- Waste heat recovery from low temperature flue gases.  
- Comparing various patents with the base case Rankine cycle.  
Out-of-Scope:  
- Car engines and other types of heat engines.  
- Geothermal springs. |
| Deliverables |  
- Business opportunity assessment (Cost analysis)  
- Technical feasibility assessment (Component availability)  
- Product life cycle |
| Time Line | To finish the project assessment by the middle of April 2010. |
### Innovation Map

<table>
<thead>
<tr>
<th>Customer-Value Proposition</th>
<th>Products</th>
<th>Technical Differentiation</th>
<th>Process / Manufacturing Technology</th>
<th>Materials Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximize Power Generation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimize Fixed Costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimize Variable Costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Products**
- Basic Rankine Cycle
- Heat Recovery Cycle
- Heat Exchanger Network Configuration

**Technical Differentiation**
- Fewest Block Components

**Process / Manufacturing Technology**
- Heat Recovery Cycle
- Refrigerants with low specific heats that are liquid at room temperature.

**Materials Technology**
- Readily Available Materials
- Materials with low specific heats.
Market and Competitive Analysis

Overview

Constituting only 5% of the world’s population, the United States consumes approximately 21% of the world’s energy (U.S. Energy Information Administration, 2010), ranking 7th in per capita energy consumption. In order to preserve the planet while maintaining the standard of living, the United States both must practice energy conservation and maximize energy production.

In the United States in 2008, over 2.4 billion metric tons of carbon dioxide were emitted into the atmosphere as a result of electricity generation (U.S. Energy Information Administration, 2009), and over 80% of these greenhouse gas emissions are energy-related. Figure 1 shows the carbon dioxide emissions of the electric power sector compared to other energy-related sectors.

![Figure 1](image)

Figure 1 shows the US energy-related carbon dioxide emissions by various sectors. Energy-related carbon dioxide emissions account for more than 80 percent of U.S. greenhouse gas emissions. (Source: EIA, 2008)

Although the relationship between carbon dioxide emissions and global warming is an ongoing debate, higher carbon dioxide levels have been shown to degrade the quality of air and cause respiratory problems such as asthma and emphysema. Figure 2 shows the part per million measurement of carbon dioxide in the atmosphere dating back to 1960. The trend of increasing atmospheric CO$_2$ is unsustainable in the long run. In addition to carbon dioxide, the burning of coal releases other toxic materials such as lead, mercury, cadmium and sulfur. Heavy metals are highly toxic to individuals because they are difficult to excrete once in the bloodstream and tend accumulate in vital organs such as the liver. Epidemiological studies presented at a 2008 American Chemical Society national meeting...
had shown that more than 500,000 Americans die each year from cardiopulmonary disease linked to breathing fine-particle air pollution (Dollemore, 2008).

Figure 2 shows the monthly mean atmospheric carbon dioxide measurements at Mauna Loa Observatory in Hawaii. The red line represents the mean monthly measurements and the black line represents seasonally corrected data. (Source: NOAA, 2010)

The production of electricity also emitted almost 8 billion metric tons of sulfur dioxide (SO$_2$) and more than 3 billion metric tons of nitrogen oxides (NO$_x$) in 2008. These gases are responsible for the acid rain that destroys plant life, kills aquatic animals and contaminates ground water. Sulfur particles account for 50 to 70 percent of the visibility reduction in the eastern United States (U.S. Environmental Protection Agency, 2007).

Therefore, processes that are able to generate additional power from waste energy sources have the potential to decrease greenhouse emissions and therefore positively benefit society and the environment. The proposed low-grade heat recovery cycle will be able to recover energy from low energy heat sources that would otherwise be released into the environment. Every day, billions of BTUs worth of heat from industrial processes are dumped into cooling water, which is then transferred back into the environment. Instead, this proposed energy cycle would be able to capture approximately 10% of this energy from heat sources at temperatures as low as 200°F, and turn it into electricity that could either be sold or utilized elsewhere in a production facility.
Market for Electricity

In 2009, electricity consumption reached 10.17 billion kW·hr per day in the United States (U.S. Energy Information Administration, 2009). 48.7% of power is generated from coal, another 21.4% from natural gas and 19.7% from nuclear power plants. As seen in Figure 3, electricity consumption is projected to increase by more than 50% in the next 20 years, meaning new power plants must be built.

Figure 3 shows growth in world electric power generation and total energy consumption from 1990 to 2030. (Source: EIA, 2010)

Currently there are 17,658 generators in the United States with an existing nameplate capacity of 1.104 billion kW. For 2010, 19.8 million kW, or 1.8%, of additional nameplate capacity is planned (U.S. Energy Information Administration, 2009). However, the cost of building a new power plant is prohibitively expensive. In 2007, Duke Energy, one of the largest U.S. utilities and most experienced builders, stated it would cost $1.83B to build a new 800,000 kW coal-fired power plant (Wald, 2007). These capital costs continue to rise as the price of raw building materials increase. For example, the price of steel, copper and nickel have more than doubled in the last decade as demand from developing nations such as China, India and Brazil drive up prices.

Therefore, as the cost of building new power plants increases dramatically, it will become more appealing to find ways to generate marginal electricity. This low-grade heat recovery cycle offers the opportunity to recover marginal electricity from waste heat sources in existing power plants. If only 10% of the existing 17,658 generators adopted this process, it will potentially generate 3.179 million kW of
additional capacity, or 16.1% of the planned 2010 new capacity, without having to build new plants. The cost of building these new facilities is $5.7B. Using the costs provided by Duke Energy, the projected cost of building new facilities to produce the same amount of power will be $5.47B. Although the cost of building the new facilities is marginally higher than building a power plant, it saves this energy from being released into the environment because under normal circumstances, this waste heat is dumped into a heat sink such as cooling water. The low-grade heat recovery cycle reduces thermal pollution from the generation of electricity in addition to reducing CO$_2$, SO$_2$ and NO$_x$ emissions.
Process Design

Customer Requirements

The most important part of designing the heat recovery cycle is to understand the demands of the customer, which will determine the goals for the project. For this design, the customer is a chemical or power plant that produces a waste heat stream consisting of 65,000 lb-mol/hr of air at 230°F and 120psi. The customer desires to extract power from this stream before it is discarded as waste heat, which makes it a low-grade heat recovery case.

Ammonia is suggested as the working fluid, but other fluids could be explored. The organic Rankine cycle is suggested as a starting point, and the cycle in US Patent 7,278,264 as another alternative. The heat exchanger is recommended to be a plate-and-fin model with a minimum temperature approach of 2°F with 20 Number of Transfer Units (NTUs).

In addition, there are some concerns regarding cost, the environment and safety with the project, which were taken into consideration when choosing the appropriate refrigerant for the recovery cycle. The process is supposed to be low-cost in order for it to be viable as an attachment to a plant, and cannot require much maintenance. It also has to be safe and environmentally conscious, in order to fit current and future industry and government standards.

Process Selection

Organic Rankine Cycle

The first design considered for the low-grade heat recovery process was the basic organic Rankine cycle (Figure 4). The original Rankine cycle is a thermodynamic cycle that converts thermal energy into work. It consists of water within a closed loop, which absorbs heat from an external stream through a heat exchanger. The power is recovered through the expansion of this heated stream across a turbine, and little power is consumed in the pump because the fluid is liquid when it gets pressurized. By condensing the vapor phase component into liquid through the condenser, the work required by the pump consumes only 1-3% of the turbine power and contributes to a much higher efficiency for a real cycle. (Seider, 2009)

The Organic Rankine Cycle (ORC) is characterized by the use of an organic fluid as the cycle’s working fluid. The desired characteristics for this fluid are a high molecular mass and low boiling point,
and therefore the ones more commonly used are ammonia and specifically designed refrigerants. These refrigerants are usually composed of different combinations of carbon, fluorine, chlorine and hydrogen. These specific characteristics allow the fluid to capture heat from low-energy sources, such as waste heat streams, justifying its choice as the base-case for this project.

Figure 4 shows a typical Organic Rankine Cycle (ORC). A liquid working fluid steam (3) is heated using energy from a hot stream (1) and then expanded into a vapor-liquid phase to produce electricity. The vapor-liquid stream (5) is then condensed back into a pure liquid and pumped back into the heat exchanger.

The cycle consists of four steps: heating, expansion, condensing and pressurizing. Initially, the organic fluid is a liquid at high pressure, entering the heat exchanger (stream 3) countercurrent to the hot stream (stream 1). In the heat exchanger, the working fluid absorbs energy from the hot stream as latent heat and vaporizes. The hot stream leaves the heat exchanger and exits at a lower temperature (stream 2). Meanwhile, the organic fluid that leaves as saturated vapor (stream 4) passes through an expander (turbine), where it generates power through a pressure drop. The stream leaving the expander (stream 5) is at a lower pressure, lower temperature, and partially liquefied. To minimize pumping issues, the fluid is condensed at constant pressure before being pumped. For this purpose, a shell and tube heat exchanger may be used, or a cooling tower. The fluid leaves the condenser as a saturated liquid (stream 6) and is pumped again to high pressures (stream 3).

**Improvement to Organic Rankine Cycle using Dense Fluid Expander**

As an improvement to this cycle, Mr. Adam Brostow from Air Products and Chemicals Inc. filed the US Patent 7,278,264, with an improved low-grade heat recovery cycle (Figure 7 with original patent.
stream numbers). The main differentiating feature between this cycle and the basic organic Rankine cycle is that in this case, the working fluid is not vaporized through the heat exchanger, making for a more thermodynamically efficient exchange between the streams, as shown by the cooling curves in Figure 5 and Figure 6.

Figure 5 shows the cooling curve for a thermodynamically inefficient heat exchanger. Notice how the hot and cold streams do not follow each other closely.

Figure 6 shows the cooling curve for a thermodynamically efficient heat exchanger. Notice how the hot and cold streams follow each other closely.
In this cycle, stream 120 enters the heat exchanger as a low-temperature, high pressure liquid, and is heated countercurrent to the hot stream (114). The working fluid exits as stream 122, a high-temperature high-pressure liquid, which is then partially vaporized through a dense liquid expander (unit 124) to generate power. The resulting mixed stream is at mid-pressure and mid-temperature, and is separated in a flash evaporator (unit 326). The vapor stream (stream 327) is once again heated countercurrent to the hot stream in the heat exchanger, which it only transverses partially, to become mid-pressure, high temperature (stream 328). This stream is then once again expanded through a vapor expander (unit 330) to generate more power, and it leaves as a low-pressure, low-temperature vapor. In addition, the liquid stream leaving the evaporator (334) is expanded across another liquid expander (unit 336) and becomes partially vaporized, resulting in stream 338 that is a low-pressure, low-temperature vapor-liquid mixture. Stream 338 is then mixed with stream 332 to form stream 340, that is then condensed across a shell and tube exchanger (unit 130) to become a low-pressure, low-temperature liquid (stream 131). The liquid is then pressurized across a pump to become high-pressure, low-temperature liquid (stream 120), which then goes into the heat exchanger to close the cycle.

Figure 7 shows US Patent 7,278,264 filed by Mr. Adam Brostow of Air Products and Chemicals Inc. as an improvement to the Organic Rankine Cycle (ORC).
Improvement to Organic Rankine Cycle using Second Flash Evaporator

In considerations relating to the efficiency of the cycle as a whole, the design team suggested an improvement on Mr. Brostow’s patent, shown in Figure 8. This improvement consists of the addition of a second flash evaporator (unit 339), to separate stream 338 into a vapor (342) and a liquid (341) stream. The liquid stream can then bypass the condenser, joining condensed streams 342 and 332 before being pumped. This improvement may be significant especially in cases where the size of the condenser is a concern in the project, and where it would be more beneficial to add an additional piece of equipment (the flash evaporator) than to have to condense a vapor-liquid mixture through a shell and tube heat exchanger, which may be impractical. In cases where a cooling tower is used to reject heat to the environment, this modification is unnecessary.

Figure 8 shows this team’s improvements to US Patent 7,278,264. The addition of flash vaporization column 339 reduces the cooling utility required in condenser 130.
Heat Exchanger Design

Considerations in Heat Exchanger Design

Considerations in heat exchanger design are essential for maximum heat transfer from the energy source to the chosen working fluid. The most common design is when two streams are separated from each other by a wall through which energy, but not mass, can pass (Koretsky). Multi-stream exchange systems are also feasible.

Figure 9 shows the exploded view of a brazed aluminum heat exchanger, also known as a plate and fin heat exchanger. (Source: http://www.lytron.com/tools_technical/notes/titanium_heat_exchangers.aspx)

The most important considerations are the heat duty of the hot stream and the variation of enthalpy with intermediate conditions in the exchanger. $Q$ is the overall heat duty rate, $\dot{m}$ is the mass flow, while $\tilde{H}$ notes the specific enthalpy value.

(Eq. 1) \[ Q = \dot{m} (\tilde{H}_{\text{out}} - \tilde{H}_{\text{in}}) \]

The variation is represented most conveniently by heating and cooling curves. Heat is transferred to and from process streams using heat-transfer media, also referred to as coolants or heat sources. In the current project scenario, air is the heat source, while a chosen refrigerant is the coolant. The selection of appropriate heat transfer media has been included later in the report. (Seider, 2009)
Available Heat Exchanger Models

A variety of heat exchanger models are employed in current industry. The most common types are shell-and-tube heat exchangers. Heat transfer area per unit volume is greatly increased by placing a large number of small-diameter tubes inside a shell. These units can be employed as large scale condensers to exchange heat with cooling water (Seider, 2009). However, the design team found that for the purposes of low-grade heat recovery, heat recovery via shell-and-tube heat exchangers would not suffice economically and thermodynamically.

With the recommendation of Air Products consultant Adam Brostow, the design team explored the utility of plate-fin heat exchangers. The plate-fin heat exchangers were found to have many advantages over the shell & tube design. Economically, the high ratio of effective heat exchange surface-to-weight-and-size yields lower unit cost. Additional savings occur due to reduced pressure drop losses. The design is compact, and provides approximately nine times more heat exchange surface area than would be available in a typical shell and tube unit. Multiple fluid streams and a variety of flow patterns can be accommodated. (Stewart-Warner, 1984)

Higher available heat transfer surface area make the plate-fin model more suitable for low-grade heat recovery considering the margins of energy available in the current project.

Design

The suggested patent design recommends the use of a plate-fin heat exchanger that can handle three streams. Stream 114 is the incoming hot stream, while Stream 120 and Stream 327 are the incoming cold streams. The flow pattern chosen is counter-flow where the fins are arranged so that the flow channels are parallel and the hot and cold streams flow in opposite directions. The fin material is aluminum. The selection of the most suitable fins is dependent on the maximum working pressure, fluid flow rates, and allowable pressure drops. Separator layers are used to separate each layer of fin matrices to meet design pressure requirements. For pressures of 450 psig or higher, a separator sheet thickness of .064 inches is recommended.

ASPEN Simulations determined the values of heat duty Q, mean temperature difference MTD, and UA. Using a mass flux value of 300,000 lb/hr-ft² suggested by Professor Fabiano, the design team researched fluid properties to design the physical heat exchanger for ammonia.

The design team agreed upon using a hybrid of the shortcut method and correlations from the Stewart-Warner design pamphlet in order to assemble the heat exchanger. The design team picked fin
heights of 0.375 inches, fin spacing of 20, fin thicknesses of 0.008 inches, and a perforated surface to maximize heat transfer and to provide the durability at high pressures to prevent buckling. Free stream factors of 0.002140, and heat transfer area factors of 0.939 were also incorporated. The hydraulic radius was estimated at 0.002 inches for primary design purposes. (Stewart-Warner, 1984)

In order to determine the correct Colburn factors \( j \) for heat-transfer calculation purposes, the design team calculated the Reynolds number of each stream and used the correlations from Figure 10 (Stewart-Warner, 1984) to determine values. The heat transfer coefficients could then be determined. (Stewart-Warner)

![Figure 10](image_url)

**Figure 10** shows the correlation between the Colburn factor, \( j \), and Reynolds number for a plate and fin heat exchanger utilizing perforated fins of 0.375” height, 8 Fins/inch – 0.025” thick. (Source: Stewart-Warner)

Using the shortcut method, the heat transfer coefficient of each stream was calculated. The heat transfer coefficient was 4.26 kW/m\(^2\)-K for stream 114, 13.90 kW/m\(^2\)-K for stream 120, and 4.522742 kW/m\(^2\)-K. The overall heat transfer coefficient was calculated to be 189 W/m\(^2\)-K. From the UA value of 4019.7 kW/K calculated earlier by ASPEN, the surface area required was calculated to be 21207.02 m\(^2\). Available plate-fin heat exchangers from Chart guarantee areas of 1000-1500 m\(^2\)/m\(^3\) (Chart,2010). Thus the required volume of the core was found to be 21.20702 m\(^3\) using the procedure.
from Stewart-Warner design pamphlet. Compared to the shortcut method estimation, Stewart-Warner’s design is 52.4% more compact and is favorable for handling.

The surface area requirement for heat transfer is 228,270.50 ft$^2$. The overall dimensions recommended for a plate-fin heat exchanger unit are 12 feet length by 5.5 feet width by 5.5 feet height. The number of layers was determined by accounting for the fin height and separator plate thicknesses and dividing by the height of the heat exchanger. With 0.375 inch-fin heights and .064 separators, approximately 166 layers of fins are required. With fin thicknesses of approximately 0.008 inches with about 8 fins covering each inch, there are approximately 524 fins across each layer. Approximately 86,888 12-foot long micropassages are available for heat transfer. Therefore, this model provides approximately 86,833 ft$^2$ of heat transfer area. Considering the total transfer area required and heat transfer efficiencies of 95% (Stewart-Warner, 1984) to account for the estimated fouling factors, the design team needs 3 units of plate-fin heat exchangers in series to optimize heat recovery.

To maximize heat transfer efficiency, the design team has decided to alternate Stream 120, Stream 114, and Stream 327 in a forward, reverse, and forward flow direction pattern from the top layer to the bottom layer.

**Working Fluid Analysis**

When analyzing possible candidates for refrigerants for the organic Rankine cycle, a few considerations were partaken. Some of these considerations include heat capacity, toxicity, and cost. Based on the availability of some commonly used refrigerants, the following refrigerants were selected for further study: R-134a, R-245, propane, pentane, carbon dioxide and ammonia. Table 1 and Table 2 show the important physical properties and structures, respectively.

**R-134a**

R-134a is also known as 1,1,1,2-tetrafluoroethane. It is an inert gas typically used in domestic refrigeration in such devices as home refrigerators and automobile air conditioners. As for safety, it is not flammable at operating temperatures and is not toxic (Franklin, 1993)

**R-245**

R-245 is also known as pentafluoropropane and has a molecular formula of C$_3$H$_5$F$_5$. It is another refrigerant that is used more often in commercial refrigeration processes. In small quantities it is not harmful and not flammable at the operating temperatures (Grebenkov, Tsurbelev, Beliaeva, & Timofeyev).
Propane

Propane is typically a fuel, but has utility as a refrigerant. The benefits to propane are mostly environmental. The ozone depletion potential is low and the global warming potential is also low. Propane is not toxic at low levels. However, propane is a fuel and is extremely flammable.

Pentane

Pentane is another simple hydrocarbon that is often used in refrigerant blends. It is used in its pure state for these analyses. Like propane, pentane is more environmentally friendly than other refrigerants. It is not toxic at low levels, but is very flammable.

Carbon Dioxide

Carbon dioxide was widely used before the introduction of Freon. Carbon dioxide no more widely used because of the high pressures required to have it work properly as a refrigerant. This would require high pressure-resistant machinery. From an economic standpoint, unless there is already equipment that can handle the necessary operating pressures and temperatures, it is usually not a sustainable system. CO$_2$ is being looked again in industry, but at as a next generation refrigerant because of the low environmental impacts it has (Modine, 2008). CO$_2$ is only slightly hazardous to one’s health in small levels and very hazardous at higher levels. It is not flammable.

Ammonia

Ammonia has long been a standard refrigerant in the industrial area. It is most revered for its vaporization properties. It is also highly energy efficient and has a low cost. It is not preferred because of its environmental impact. Ammonia is highly toxic and has been phased out in many applications due to its toxicity and due to environmental concerns. Many long-term health risks have been linked to ammonia exposure, so special precautions would need to be taken for a system with ammonia (Appl, 2006).
Table 1 shows the molecular weights and specific heats of the various refrigerants.

<table>
<thead>
<tr>
<th>Refrigerant Name</th>
<th>Chemical Formula</th>
<th>Molecular Weight</th>
<th>Specific Heat of Liquid Phase at STP (unless otherwise specified)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R134a</td>
<td>C$_2$H$_2$F$_4$</td>
<td>102.031</td>
<td>0.3391 Btu/lb-°F</td>
</tr>
<tr>
<td>R245</td>
<td>C$_3$H$_3$F$_5$</td>
<td>134.049</td>
<td>0.0788 Btu/lb-°F</td>
</tr>
<tr>
<td>Propane</td>
<td>C$_3$H$_8$</td>
<td>44.096</td>
<td>0.5294 Btu/lb-°F</td>
</tr>
<tr>
<td>Pentane</td>
<td>C$<em>5$H$</em>{12}$</td>
<td>72.15</td>
<td>0.5533 Btu/lb-°F</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>CO$_2$</td>
<td>44.01</td>
<td>0.2876 Btu/lb-°F (at 100°F and 357 psia)</td>
</tr>
<tr>
<td>Ammonia</td>
<td>NH$_3$</td>
<td>17.03</td>
<td>1.1330 Btu/lb-°F</td>
</tr>
</tbody>
</table>
Table 2 shows the chemical structure of the various refrigerants.

<table>
<thead>
<tr>
<th>Refrigerant Name</th>
<th>Chemical Formula</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>R134a</td>
<td>C₂H₂F₄</td>
<td><img src="image" alt="Structure of R134a" /></td>
</tr>
<tr>
<td>R245</td>
<td>C₃H₃F₅</td>
<td><img src="image" alt="Structure of R245" /></td>
</tr>
<tr>
<td>Propane</td>
<td>C₃H₈</td>
<td><img src="image" alt="Structure of Propane" /></td>
</tr>
<tr>
<td>Pentane</td>
<td>C₅H₁₂</td>
<td><img src="image" alt="Structure of Pentane" /></td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>CO₂</td>
<td><img src="image" alt="Structure of Carbon Dioxide" /></td>
</tr>
<tr>
<td>Ammonia</td>
<td>NH₃</td>
<td><img src="image" alt="Structure of Ammonia" /></td>
</tr>
</tbody>
</table>
Use of Different Refrigerants as Organic Fluids

In addition to a different cycle, the design team also studied different refrigerants, in addition to ammonia, to be used in the process. These included propane, pentane, carbon dioxide, Refrigerant 134a and Refrigerant 245. Carbon dioxide was discarded because for it to be liquid for most of the cycle it would have to be kept at low temperatures and high pressures, which makes it impractical for the customer requirements. Pentane and propane were discarded because they showed the least promise of net energy production.

For the next three refrigerants, a sensitivity analysis was done based on ASPEN models, which were made for each refrigerant based on the original patent, with four different pump outlet pressures. The results compiled from these tests are shown in Table 3, with required flow rate and net power obtained.

Table 3 shows sensitivity analysis performed using ASPEN to determine the maximum amount of net power able to be generated with various working fluids at various pressures.

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>300</th>
<th>500</th>
<th>700</th>
<th>900</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ammonia</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molar flow rate (lbmol/hr)</td>
<td>57,000</td>
<td>30,900</td>
<td>22,100</td>
<td>17,500</td>
</tr>
<tr>
<td>Mass flow rate (lb/hr)</td>
<td>970,739</td>
<td>526,245</td>
<td>376,375</td>
<td>298,035</td>
</tr>
<tr>
<td>Net Power (MW)</td>
<td>0.72</td>
<td>1.18</td>
<td>1.54</td>
<td>1.82</td>
</tr>
<tr>
<td><strong>134a</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molar flow rate (lbmol/hr)</td>
<td>19,200</td>
<td>9,991</td>
<td>9,100</td>
<td>10,267</td>
</tr>
<tr>
<td>Mass flow rate (lb/hr)</td>
<td>1,959,000</td>
<td>1,019,358</td>
<td>928,848</td>
<td>1,047,510</td>
</tr>
<tr>
<td>Net Power (MW)</td>
<td>1.17</td>
<td>1.79</td>
<td>1.89</td>
<td>1.76</td>
</tr>
<tr>
<td><strong>245</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molar flow rate (lbmol/hr)</td>
<td>11,200</td>
<td>7,000</td>
<td>7,900</td>
<td>8,400</td>
</tr>
<tr>
<td>Mass flow rate (lb/hr)</td>
<td>1,501,351</td>
<td>938,342</td>
<td>1,058,986</td>
<td>1,126,011</td>
</tr>
<tr>
<td>Net Power (MW)</td>
<td>1.59</td>
<td>2.04</td>
<td>1.92</td>
<td>1.83</td>
</tr>
</tbody>
</table>

From these results, the team was able to identify the two most promising models, ammonia at 900psi when leaving the pump and Refrigerant 245 at 500psi when leaving the pump. Ammonia was
chosen because it is cheaper and more readily available, and the amount required in pounds is over 3 times lower than both refrigerants. As a second option, Refrigerant 245 at 500psi was chosen because it presented the most promising power output. All subsequent patent results are based on these models.

However, when considering the fact that the ammonia would be highly pressurized throughout the entire cycle, which would increase the risk of leakage, the design group decided to explore lower-pressure alternatives. Even though this was outside of the scope of the project, similar conditions for the amount of ammonia, the hot stream outlet conditions, and the pump outlet pressure could generate the same amount of power (1.8MW) if 22% of the ammonia was vaporized through the heat exchanger. Under these conditions, the pump would potentially be more affordable and the piping would be less of an expense. Additionally, there would be fewer health and environmental concerns, considering lower pressure ammonia is less likely to leak from equipment.

**Design Evolution**

**Different Refrigerants in the Basic Organic Rankine Cycle**

Initially, based on customer requirements, the design group began working on the basic organic Rankine cycle (Figure 4) with ammonia as a refrigerant. The stream characteristics were added as suggested by the patent (as opposed to the refrigerant and pressure sensitivity analysis described above), given the appropriate proportions. The resulting stream details are listed in Table 4.

**Table 4** shows the various stream characteristics for the Organic Rankine Cycle using Ammonia as the working fluid.

<table>
<thead>
<tr>
<th>Stream Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td>Air</td>
<td>Air</td>
<td>Ammonia</td>
<td>Ammonia</td>
<td>Ammonia</td>
<td>Ammonia</td>
</tr>
<tr>
<td>State</td>
<td>Vapor</td>
<td>Vapor</td>
<td>Liquid</td>
<td>Vapor</td>
<td>Mixed</td>
<td>Liquid</td>
</tr>
<tr>
<td>Vapor fraction</td>
<td>1.00</td>
<td>1.00</td>
<td>0.00</td>
<td>1.00</td>
<td>0.90</td>
<td>0.00</td>
</tr>
<tr>
<td>Mass flow (lb/hr)</td>
<td>1,880,000.0</td>
<td>1,880,000.0</td>
<td>59,600.0</td>
<td>59,600.0</td>
<td>59,600.0</td>
<td>59,600.0</td>
</tr>
<tr>
<td>Volume flow (cuft/hr)</td>
<td>4,020,000.0</td>
<td>3,600,000.0</td>
<td>1,576.4</td>
<td>28,700.0</td>
<td>129,000.0</td>
<td>1,571.7</td>
</tr>
<tr>
<td>Temperature (F)</td>
<td>230.0</td>
<td>159.6</td>
<td>72.2</td>
<td>179.7</td>
<td>70.1</td>
<td>70.1</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>120.0</td>
<td>120.0</td>
<td>628.6</td>
<td>628.6</td>
<td>128.6</td>
<td>128.6</td>
</tr>
</tbody>
</table>

Using the same design, the team used Refrigerant 245 for the basic organic Rankine cycle. The resulting streams are shown in Table 5.
Table 5 shows the various stream characteristics for the Organic Rankine Cycle using Refrigerant 245 as the working fluid.

<table>
<thead>
<tr>
<th>Stream Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td>Air</td>
<td>Air</td>
<td>245</td>
<td>245</td>
<td>245</td>
<td>245</td>
</tr>
<tr>
<td>State</td>
<td>Vapor</td>
<td>Vapor</td>
<td>Liquid</td>
<td>Vapor</td>
<td>Vapor</td>
<td>Liquid</td>
</tr>
<tr>
<td>Vapor fraction</td>
<td>1.00</td>
<td>1.00</td>
<td>0.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Mass flow (lb/hr)</td>
<td>1,880,000.0</td>
<td>1,880,000.0</td>
<td>134,000.0</td>
<td>134,000.0</td>
<td>134,000.0</td>
<td>134,000.0</td>
</tr>
<tr>
<td>Volume flow (cuft/hr)</td>
<td>4,020,000.0</td>
<td>389,000.0</td>
<td>1,804.1</td>
<td>6,178.5</td>
<td>95,200.0</td>
<td>1,793.2</td>
</tr>
<tr>
<td>Temperature (F)</td>
<td>230.0</td>
<td>208.2</td>
<td>68.9</td>
<td>223.5</td>
<td>80.1</td>
<td>65.1</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>120.0</td>
<td>120.0</td>
<td>450.0</td>
<td>450.0</td>
<td>55.0</td>
<td>55.0</td>
</tr>
</tbody>
</table>

For this process, the net amount of power recovered, considering both the gain from the expander and the input to the pump, was approximately 1MW for ammonia and 0.5MW for Refrigerant 245. Hoping to improve on those results, the design team applied similar inputs to the ASPEN model for the original patent, filed by Mr. Brostow and Air Products (Figure 7). However, the optimal pressure at the pump outlet was determined to be 900psi for ammonia and 500psi for Refrigerant 245, based on the results from the design team's sensitivity analysis for refrigerants and pressures.

**Different Refrigerants in the Patented Cycle**

With the patent design, the stream characteristics found when running the simulation for ammonia were the ones displayed in Table 6. The net amount of work produced in this cycle was 1.8MW, which shows 80% improvement from the basic organic Rankine cycle.
Table 6 shows the various stream characteristics for the modified Rankine Cycle (US Patent 7,278,264) using Ammonia as the working fluid.

<table>
<thead>
<tr>
<th>Stream Number</th>
<th>114</th>
<th>118</th>
<th>120</th>
<th>122</th>
<th>126</th>
<th>131</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td>Air</td>
<td>Air</td>
<td>Ammonia</td>
<td>Ammonia</td>
<td>Ammonia</td>
<td>Ammonia</td>
</tr>
<tr>
<td>State</td>
<td>Vapor</td>
<td>Vapor</td>
<td>Liquid</td>
<td>Liquid</td>
<td>Mixed</td>
<td>Liquid</td>
</tr>
<tr>
<td>Vapor fraction</td>
<td>1.00</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.29</td>
<td>0.00</td>
</tr>
<tr>
<td>Mass flow (lb/hr)</td>
<td>1,880,000.0</td>
<td>1,880,000.0</td>
<td>298,000.0</td>
<td>298,000.0</td>
<td>298,000.0</td>
<td>298,000.0</td>
</tr>
<tr>
<td>Volume flow (cuft/hr)</td>
<td>4,016,000.0</td>
<td>3,300,000.0</td>
<td>7,890.2</td>
<td>10,400.0</td>
<td>118,000.0</td>
<td>7,855.8</td>
</tr>
<tr>
<td>Temperature (F)</td>
<td>230.0</td>
<td>85.9</td>
<td>72.9</td>
<td>209.9</td>
<td>109.0</td>
<td>69.8</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>120.0</td>
<td>115.0</td>
<td>900.0</td>
<td>895.0</td>
<td>244.6</td>
<td>129.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stream Number</th>
<th>327</th>
<th>328</th>
<th>332</th>
<th>334</th>
<th>338</th>
<th>340</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td>Ammonia</td>
<td>Ammonia</td>
<td>Ammonia</td>
<td>Ammonia</td>
<td>Ammonia</td>
<td>Ammonia</td>
</tr>
<tr>
<td>State</td>
<td>Vapor</td>
<td>Vapor</td>
<td>Vapor</td>
<td>Liquid</td>
<td>Mixed</td>
<td>Mixed</td>
</tr>
<tr>
<td>Vapor fraction</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.00</td>
<td>0.09</td>
<td>0.38</td>
</tr>
<tr>
<td>Mass flow (lb/hr)</td>
<td>87,800.0</td>
<td>87,800.0</td>
<td>87,800.0</td>
<td>210,000.0</td>
<td>210,000.0</td>
<td>298,000.0</td>
</tr>
<tr>
<td>Volume flow (cuft/hr)</td>
<td>113,000.0</td>
<td>144,000.0</td>
<td>239,000.0</td>
<td>5,872.1</td>
<td>49,900.0</td>
<td>272,000.0</td>
</tr>
<tr>
<td>Temperature (F)</td>
<td>108.7</td>
<td>209.9</td>
<td>130.1</td>
<td>108.7</td>
<td>70.2</td>
<td>70.2</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>243.6</td>
<td>238.6</td>
<td>129.0</td>
<td>243.6</td>
<td>129.0</td>
<td>129.0</td>
</tr>
</tbody>
</table>

A second simulation using the patent was run, this time with Refrigerant 245 pumped to a pressure of 500psi at the pump outlet. The stream results are displayed in Table 7. This design is predicted to generate 2MW of power, 100% more than the basic organic Rankine cycle with ammonia, and 400% more than the organic Rankine cycle with Refrigerant 245.
Table 7 shows the various stream characteristics for the modified Rankine Cycle (US Patent 7,278,264) using Refrigerant 245 as the working fluid.

<table>
<thead>
<tr>
<th>Stream Number</th>
<th>114</th>
<th>118</th>
<th>120</th>
<th>122</th>
<th>126</th>
<th>131</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td>Air</td>
<td>Air</td>
<td>245</td>
<td>245</td>
<td>245</td>
<td>245</td>
</tr>
<tr>
<td>State</td>
<td>Vapor</td>
<td>Vapor</td>
<td>Liquid</td>
<td>Liquid</td>
<td>Mixed</td>
<td>Liquid</td>
</tr>
<tr>
<td>Vapor fraction</td>
<td>1.00</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.60</td>
<td>0.00</td>
</tr>
<tr>
<td>Mass flow (lb/hr)</td>
<td>1,880,000.0</td>
<td>1,880,000.0</td>
<td>938,000.0</td>
<td>938,000.0</td>
<td>938,000.0</td>
<td>938,000.0</td>
</tr>
<tr>
<td>Volume flow (cuft/hr)</td>
<td>4,020,000.0</td>
<td>3,300,000.0</td>
<td>12,700.0</td>
<td>22,900.0</td>
<td>83,900.0</td>
<td>12,700.0</td>
</tr>
<tr>
<td>Temperature (F)</td>
<td>230.0</td>
<td>85.9</td>
<td>74.1</td>
<td>223.8</td>
<td>168.2</td>
<td>70.0</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>120.0</td>
<td>115.0</td>
<td>500.0</td>
<td>495.0</td>
<td>244.6</td>
<td>60.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stream Number</th>
<th>327</th>
<th>328</th>
<th>332</th>
<th>334</th>
<th>338</th>
<th>340</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td>245</td>
<td>245</td>
<td>245</td>
<td>245</td>
<td>245</td>
<td>245</td>
</tr>
<tr>
<td>State</td>
<td>Vapor</td>
<td>Vapor</td>
<td>Vapor</td>
<td>Liquid</td>
<td>Mixed</td>
<td>Vapor</td>
</tr>
<tr>
<td>Vapor fraction</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.00</td>
<td>0.53</td>
<td>1.00</td>
</tr>
<tr>
<td>Mass flow (lb/hr)</td>
<td>561,000.0</td>
<td>561,000.0</td>
<td>561,000.0</td>
<td>377,000.0</td>
<td>377,000.0</td>
<td>938,000.0</td>
</tr>
<tr>
<td>Volume flow (cuft/hr)</td>
<td>78,200.0</td>
<td>102,000.0</td>
<td>433,000.0</td>
<td>6,311.3</td>
<td>127,000.0</td>
<td>594,000.0</td>
</tr>
<tr>
<td>Temperature (F)</td>
<td>167.9</td>
<td>223.8</td>
<td>160.0</td>
<td>167.9</td>
<td>70.1</td>
<td>73.1</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>243.6</td>
<td>238.6</td>
<td>60.0</td>
<td>243.6</td>
<td>60.0</td>
<td>60.0</td>
</tr>
</tbody>
</table>

Different Refrigerants in the Design Team Cycle

Finally, with the improvements suggested by the design team, as shown in Figure 8, a third simulation was built for both ammonia and R-245, again with a pressure at the pump outlet of 900psi and 500psi, respectively. For this simulation, the pressures and temperatures were the same as the ones for the original patent simulation, with the exception of the added streams and process unit. For this cycle, the net amount of energy generated is the same or slightly lower as it would have been with the original patent design, due to the added pressure drop across another flash vaporizer. However, as highlighted in the stream results in Table 8 and Table 9, the amount of fluid going through the condenser is significantly reduced. Whereas in the original ammonia cycle, there were 298,000 pounds per hour going through the condenser, in this model there are only 107,000 pounds per hour. Similarly, in the original Refrigerant 245 cycle there were 938,000 pounds per hour going through the condenser,
versus 760,000 pounds per hour in the new model. This difference may mean a smaller heat exchanger, as well as one with less vapor-liquid mixture issues, which is beneficial to the process. The full stream results for ammonia can be seen in Table 8. Table 9 shows the results for Refrigerant 245.

Table 8 shows the various stream characteristics for the Design Team Modified Ranking Cycle using ammonia as the working fluid.

<table>
<thead>
<tr>
<th>Stream Number</th>
<th>114</th>
<th>118</th>
<th>120</th>
<th>122</th>
<th>126</th>
<th>131</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td>Air</td>
<td>Air</td>
<td>Ammonia</td>
<td>Ammonia</td>
<td>Ammonia</td>
<td>Ammonia</td>
</tr>
<tr>
<td>State</td>
<td>Vapor</td>
<td>Vapor</td>
<td>Liquid</td>
<td>Liquid</td>
<td>Mixed</td>
<td>Liquid</td>
</tr>
<tr>
<td>Vapor fraction</td>
<td>1.00</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.29</td>
<td>0.00</td>
</tr>
<tr>
<td>Mass flow (lb/hr)</td>
<td>1,880,000.0</td>
<td>1,880,000.0</td>
<td>298,000.0</td>
<td>298,000.0</td>
<td>298,000.0</td>
<td>298,000.0</td>
</tr>
<tr>
<td>Volume flow (cuft/hr)</td>
<td>4,016,000.0</td>
<td>1,300,000.0</td>
<td>7,890.2</td>
<td>10,400.0</td>
<td>118,000.0</td>
<td>7,855.8</td>
</tr>
<tr>
<td>Temperature (F)</td>
<td>230.0</td>
<td>85.9</td>
<td>72.9</td>
<td>209.9</td>
<td>109.0</td>
<td>69.8</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>120.0</td>
<td>115.0</td>
<td>900.0</td>
<td>895.0</td>
<td>244.6</td>
<td>128.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stream Number</th>
<th>327</th>
<th>328</th>
<th>332</th>
<th>334</th>
<th>338</th>
<th>340</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td>Ammonia</td>
<td>Ammonia</td>
<td>Ammonia</td>
<td>Ammonia</td>
<td>Ammonia</td>
<td>Ammonia</td>
</tr>
<tr>
<td>State</td>
<td>Vapor</td>
<td>Vapor</td>
<td>Vapor</td>
<td>Liquid</td>
<td>Mixed</td>
<td>Vapor</td>
</tr>
<tr>
<td>Vapor fraction</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.00</td>
<td>0.91</td>
<td>1.00</td>
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<tr>
<td>Mass flow (lb/hr)</td>
<td>87,800.0</td>
<td>87,800.0</td>
<td>87,800.0</td>
<td>210,000.0</td>
<td>210,000.0</td>
<td>107,000.0</td>
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<tr>
<td>Volume flow (cuft/hr)</td>
<td>113,000.0</td>
<td>144,000.0</td>
<td>240,000.0</td>
<td>5,872.1</td>
<td>49,900.0</td>
<td>286,000.0</td>
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<tr>
<td>Temperature (F)</td>
<td>108.7</td>
<td>209.9</td>
<td>129.2</td>
<td>108.7</td>
<td>70.2</td>
<td>118.7</td>
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<tr>
<td>Pressure (psi)</td>
<td>243.6</td>
<td>238.6</td>
<td>128.0</td>
<td>243.6</td>
<td>129.0</td>
<td>128.0</td>
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<table>
<thead>
<tr>
<th>Stream Number</th>
<th>341</th>
<th>342</th>
<th>343</th>
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<tbody>
<tr>
<td>Component</td>
<td>Ammonia</td>
<td>Ammonia</td>
<td>Ammonia</td>
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<tr>
<td>State</td>
<td>Liquid</td>
<td>Vapor</td>
<td>Liquid</td>
</tr>
<tr>
<td>Vapor fraction</td>
<td>0.00</td>
<td>1.00</td>
<td>0.00</td>
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<tr>
<td>Mass flow (lb/hr)</td>
<td>191,000.0</td>
<td>19,000.0</td>
<td>107,000.0</td>
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<tr>
<td>Volume flow (cuft/hr)</td>
<td>5,042.0</td>
<td>45,700.0</td>
<td>2,813.8</td>
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<tr>
<td>Temperature (F)</td>
<td>69.8</td>
<td>69.8</td>
<td>69.8</td>
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<tr>
<td>Pressure (psi)</td>
<td>128.0</td>
<td>128.0</td>
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Table 9 shows the various stream characteristics for the Design Team Modified Ranking Cycle using Refrigerant 245 as the working fluid.

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<th>Stream Number</th>
<th>114</th>
<th>118</th>
<th>120</th>
<th>122</th>
<th>126</th>
<th>131</th>
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<td>Air</td>
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<tr>
<td>State</td>
<td>Vapor</td>
<td>Vapor</td>
<td>Liquid</td>
<td>Liquid</td>
<td>Mixed</td>
<td>Liquid</td>
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<tr>
<td>Vapor fraction</td>
<td>1.00</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.60</td>
<td>0.00</td>
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<tr>
<td>Mass flow (lb/hr)</td>
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<td>1,880,000.0</td>
<td>938,000.0</td>
<td>938,000.0</td>
<td>938,000.0</td>
<td>938,000.0</td>
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<tr>
<td>Volume flow (cuft/hr)</td>
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<td>3,300,000.0</td>
<td>12,700.0</td>
<td>22,900.0</td>
<td>83,800.0</td>
<td>12,700.0</td>
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<tr>
<td>Temperature (F)</td>
<td>230.0</td>
<td>85.9</td>
<td>74.1</td>
<td>223.8</td>
<td>168.2</td>
<td>70.1</td>
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<tr>
<td>Pressure (psi)</td>
<td>120.0</td>
<td>115.0</td>
<td>500.0</td>
<td>495.0</td>
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<table>
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<tr>
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<th>328</th>
<th>332</th>
<th>334</th>
<th>338</th>
<th>340</th>
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<tbody>
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<td>245</td>
<td>245</td>
<td>245</td>
<td>245</td>
<td>245</td>
</tr>
<tr>
<td>State</td>
<td>Vapor</td>
<td>Vapor</td>
<td>Vapor</td>
<td>Liquid</td>
<td>Mixed</td>
<td>Vapor</td>
</tr>
<tr>
<td>Vapor fraction</td>
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<td>1.00</td>
<td>1.00</td>
<td>0.00</td>
<td>0.52</td>
<td>1.00</td>
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<td>561,000.0</td>
<td>561,000.0</td>
<td>377,000.0</td>
<td>377,000.0</td>
<td>760,000.0</td>
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<tr>
<td>Volume flow (cuft/hr)</td>
<td>78,100.0</td>
<td>102,000.0</td>
<td>433,000.0</td>
<td>6,313.9</td>
<td>125,000.0</td>
<td>560,000.0</td>
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<tr>
<td>Temperature (F)</td>
<td>167.8</td>
<td>223.8</td>
<td>160.0</td>
<td>167.8</td>
<td>71.0</td>
<td>137.0</td>
</tr>
<tr>
<td>Pressure (psi)</td>
<td>243.6</td>
<td>238.6</td>
<td>60.0</td>
<td>243.6</td>
<td>61.0</td>
<td>60.0</td>
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<table>
<thead>
<tr>
<th>Stream Number</th>
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<th>342</th>
<th>343</th>
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</thead>
<tbody>
<tr>
<td>Component</td>
<td>245</td>
<td>245</td>
<td>245</td>
</tr>
<tr>
<td>State</td>
<td>Liquid</td>
<td>Vapor</td>
<td>Liquid</td>
</tr>
<tr>
<td>Vapor fraction</td>
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<tr>
<td>Mass flow (lb/hr)</td>
<td>178,000.0</td>
<td>199,000.0</td>
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<td>10,250.0</td>
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<tr>
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<td>70.1</td>
<td>70.1</td>
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<tr>
<td>Pressure (psi)</td>
<td>60.0</td>
<td>60.0</td>
<td>60.0</td>
</tr>
</tbody>
</table>

In order to choose between ammonia and Refrigerant 245, the design group put together the specifications for the equipment in both cases, as well as considered the price of ammonia versus the price of the R-245 in addition to safety and environmental risks. Even though there are more serious health and environmental concerns with the use of ammonia, it is cheaper and more readily available.
than Refrigerant 245. In addition, the amount of ammonia required would be considerably less than the amount of Refrigerant 245 required, which influences how big the equipment and the piping would have to be. With all these considerations in mind, the more appropriate choice for this project seemed to be ammonia.

When choosing the optimal method of cooling the working fluid, the designs considered were a shell and tube exchanger with cooling water and evaporation of cooling water through a cooling tower. Due to the prohibitive size of the cooling tower necessary for the project, the shell and tube design was chosen. The size of the shell and tube exchanger was significantly affected by the design team’s suggestion to decrease the amount of fluid going through the condenser, making it a feasible and more attractive option. In this design, the cooling water is heated by only 3°F, which means river water could be used and returned to the river without major environmental concerns.

The costs of cooling water can be substantially eliminated by using sea water instead of freshwater to condense the working fluid. On average, seawater in the world’s oceans has a salinity of about 3.5%. The average density of seawater at the ocean surface is 1.025 grams per millilitre which compares with the average density of freshwater. (Gale 2006) Therefore, if water were to be retrieved from the ocean surface it could act as a free substitute. Considering the duration of the process is 20 operating years, and the large flow rates through both sides of the condenser, the design team determined that salt build up and equipment damage should be insignificant. Therefore, seawater was determined as an appropriate heat sink.
Process Flow Sheet

Figure 11 shows the Visio drawing of the modified Organic Rankine Cycle.
Figure 12 shows the ASPEN diagram of the modified Organic Rankine Cycle.
Process Description

For this process, 298,000 lb/hr of ammonia are used, to recover heat from a stream of 1,882,000 lb/hr of hot air.

Working fluid stream 120 enters the heat exchanger at 73°F and 900psi, and is heated countercurrent to the hot stream 114, at 230°F and 120psi.

The hot stream exits as stream 118, at a temperature of 85.6°F and 115psi.

The working fluid exits as stream 122, at 210°F and 895psi, which is then partially vaporized through a dense liquid expander (unit 124) to generate power.

The resulting mixed stream is at 109°F and 245psi and contains 28.6% vapor. It is then separated in a flash column (unit 326).

The vapor and liquid streams (327 and 334) leave the flash column at 109°F and 244psi.

The vapor stream is then once again heated countercurrent to the hot stream in the heat exchanger, which it transverses only partially. It then comes out as stream 238, at 210°F and 239psi.

Stream 238 is then expanded again through a vapor expander (unit 330), this time down to 129°F and 128psi, and comes out as stream 332.

Liquid stream (334) is expanded again through another liquid expander (unit 336) and becomes partially vaporized, resulting in stream 338 that is at 70°F and 129psi and contains 9% vapor.

Stream 338 is then split into a vapor and a liquid stream (342 and 341) in another flash column (unit 339). The output streams are at 70°F and 128psi.

Stream 342 is mixed with stream 332 to become stream 340, which is at 119°F and 128psi.

Stream 340 is then condensed across a shell and tube exchanger (unit 130) to become stream 343, which is at 70°F and 128psi, with a vapor fraction of 0%.

Stream 343 is then mixed with stream 341 to form stream 131, which is at 70°F and 128psi.
Stream 131 is then pumped back to 73°F and 900psi across the pump (unit 132) to become stream 120 again.
Equipment List and Unit Descriptions

The equipment necessary for this cycle include: the main plate and fin heat exchanger, a dense liquid expander, a liquid expander, a vapor expander, two flash vessel units, a shell and tube heat exchanger as a condenser, and a pump.

The specifications for each required unit can be found below.

**Heat Exchanger Unit 116**

The main heat exchanger provides the exchange of heat between pressurized liquid working fluid (stream 120), mid-pressure vapor (stream 327), and the incoming hot stream (stream 114). To achieve the desired heat exchange, unit 116 is split up into three brazed aluminum plate and fin heat exchangers. Each exchanger has an area of 87,000 sqft, and is 5.5 ft high, 5.5 ft wide and 12 ft long, and in each there are 166 layers of fins with 8 fins per inch, with a total of 524 fins per layer, making a total of 86,889 passages. The hot stream is cooled from 230°F to 86°F, the liquid cold stream is heated from 73°F to 210°F and the vapor cold stream, introduced after the first exchanger, is heated from 109°F to 210°F. There is an overall pressure drop of 5psi across the exchanger. Each brazed aluminum heat exchanger will cost $236,272.90.

**Expander Unit 124**

This dense fluid expander is the first to expand the pressurized fluid after the heat exchanger (stream 122 to stream 126) and before it is separated in the flash evaporator. This carbon-steel expander has an efficiency of 75% and produces 1,150kW of power. It provides a pressure drop of 650psi, and a temperature drop of 100°F. One unit is required, and it will cost $300,000.

**Expander Unit 330**

This vapor expander is the one that expands the vapor stream after it has been re-circulated through the heat exchanger (stream 328 to stream 332) and before it is condensed. This carbon-steel expander has an efficiency of 85% and produces 925kW of power. It provides a pressure drop of 110psi, and a temperature drop of 80°F. One unit is required, and it will cost $51,370.65.

**Expander Unit 336**

This liquid expander is the one that expands the liquid stream after it has been split from the vapor stream (stream 334 to stream 338) and before it split again. This carbon-steel expander has an
efficiency of 85% and produces 130kW of power. It provides a pressure drop of 115psi, and a temperature drop of 39°F. One unit is required, and it will cost $169,900.30.

**Pump Unit 132**

This unit requires two centrifugal pumps with two stages each to provide the desired pressure change of 771psi. These pumps change the pressure of the working fluid to pump it back into the heat exchanger (stream 131 to stream 120). The two pumps have an efficiency of 80% and consume 411kW of power. Two units are required. Each pump costs $165,123.10.

**Flash Column Unit 326**

The flash column for unit 326 separates the vapor-liquid mixture exiting the first expander (stream 126) into a vapor and a liquid stream (stream 327 and 334). To achieve the separation of the entire incoming stream of working fluid, the unit must be split into two separate vessels, each 6.5ft in diameter and 40ft tall and made of carbon steel. Each has a capacity of 1,330ft³. Each has a capacity of handling 80,000 ft³/hr. Each flash column costs $173,482.90.

**Flash Column Unit 339**

The flash column for unit 339 separates the vapor-liquid mixture exiting the second liquid expander (stream 338) into a vapor and a liquid stream (stream 342 and 341). To achieve the separation of the entire incoming stream of working fluid, the unit must be a carbon steel vessel 6.5 ft in diameter and 26 ft tall, with a capacity of 865 ft³. It can handle almost 52,000 ft³/hr. One unit is required and it will cost $92,649.13.

**Condenser Unit 130**

The unit necessary to condense the ammonia working fluid stream from 38% vapor to pure liquid (stream 340 to stream 343) is a carbon steel shell and tube heat exchanger that is 4 ft long and has 464 tubes and 6 passes, with a total working area of 1505 ft². The hot working fluid stream is cooled from 119°F to 70°F, and the cooling water stream is heated from 65°F to 68°F. One unit is required and it will cost $111,647.00.
# Specification Sheets

## PUMP-132

### Centrifugal Pump and Motor

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<th>COMP</th>
<th>Operation</th>
<th>Continuous</th>
<th>Cost</th>
<th>$165,123.10</th>
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<td></td>
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<td></td>
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### Composition

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### Materials

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<tr>
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<tr>
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<tr>
<td><strong>Tapproach:</strong></td>
<td>5 F</td>
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<td><strong>U (Heat coefficient):</strong></td>
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<td><strong>Volume Flow:</strong></td>
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<td><strong>Temperature:</strong></td>
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<td><strong>Pressure:</strong></td>
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<td><strong>Pressure Drop:</strong></td>
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<td><strong>Gm:</strong></td>
</tr>
<tr>
<td><strong>Cp:</strong></td>
</tr>
<tr>
<td><strong>k:</strong></td>
</tr>
<tr>
<td><strong>µ:</strong></td>
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<tr>
<td><strong>r(hydraulic):</strong></td>
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## EXP-124

**Liquid Expander**

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### Design Data

- **Energy Produced:** 1540 hp
- **Power Losses:** 0 hp
- **Isentropic Power Requirement:** 2053.8 hp
- **Efficiency:** 0.75
- **Head Developed (-):** 13644.4 ft-lb/lb
- **Mechanical Efficiency:** 1
- **Inlet Compressibility Factor:** 0.074018
- **Outlet Compressibility Factor:** 0.27099
- **Material:** Carbon Steel

### Composition

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### Materials

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<tr>
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### Design Data

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### Composition

<table>
<thead>
<tr>
<th>Composition</th>
<th>Intel</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

### Materials

<table>
<thead>
<tr>
<th>Materials</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream No.</td>
<td>328</td>
<td>332</td>
</tr>
<tr>
<td>Mass Flow Rate</td>
<td>87,779.89 lb/hr</td>
<td>87,779.89 lb/hr</td>
</tr>
<tr>
<td>Volumetric Flow Rate</td>
<td>144,420.10 ft³/hr</td>
<td>240,285.50 ft³/hr</td>
</tr>
<tr>
<td>Temperature</td>
<td>209.86°F</td>
<td>129.19°F</td>
</tr>
<tr>
<td>Pressure</td>
<td>238.64 psia</td>
<td>128 psia</td>
</tr>
<tr>
<td>Vapor Fraction</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
## FLASH-326

### Vertical Pressure Vessel

<table>
<thead>
<tr>
<th>Unit Operation</th>
<th>FLASH2</th>
<th>Operation</th>
<th>Continuous</th>
<th>Cost</th>
<th>$ 173,483.00</th>
</tr>
</thead>
</table>

**Design Data**

- **Unit Type:** Flash/Settler
- **Diameter:** 6.5 ft
- **Length:** 40 ft
- **Capacity:** 1327.323 ft³
- **Residence Time:** 1 min
- **Pressure Change:** 1 psia
- **Outlet Total Flow:** 118,959.01 ft³/hr
- **Per Vessel:** 79,639.00 ft³/hr
- **Total Needed:** 2
- **Material:** Carbon Steel

### Composition

<table>
<thead>
<tr>
<th></th>
<th>Intel</th>
<th>Outlet Liquid</th>
<th>Outlet Vapor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

### Materials

<table>
<thead>
<tr>
<th>Stream Number</th>
<th>Inlet Mass Flow Rate</th>
<th>Outlet Liquid Mass Flow Rate</th>
<th>Outlet Vapor Mass Flow Rate</th>
<th>lb/hr</th>
<th>ft³/hr</th>
<th>°F</th>
<th>psia</th>
</tr>
</thead>
<tbody>
<tr>
<td>126</td>
<td>298,034.80</td>
<td>210,254.90</td>
<td>87,779.89</td>
<td></td>
<td></td>
<td>109.01</td>
<td>244.64</td>
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<tr>
<td>334</td>
<td>118,301.70</td>
<td>5,872.11</td>
<td>113,086.90</td>
<td></td>
<td></td>
<td>108.74</td>
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<tr>
<td>327</td>
<td></td>
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<td>87,779.89</td>
<td></td>
<td></td>
<td>108.74</td>
<td>243.64</td>
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<table>
<thead>
<tr>
<th>Phantom</th>
<th>Vapor-Liquid</th>
<th>Liquid</th>
<th>Vapor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapor Fraction</td>
<td>0.29</td>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>Liquid Fraction</td>
<td>0.71</td>
<td>1.00</td>
<td>0</td>
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</table>
## FLASH-339
Vertical Pressure Vessel

<table>
<thead>
<tr>
<th>Unit Operation</th>
<th>Operation</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLASH2</td>
<td>Continuous</td>
<td>$114,729.60</td>
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</table>

### Design Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Unit Type</td>
<td>Flash/SETTLE</td>
</tr>
<tr>
<td>Diameter</td>
<td>6.5 ft</td>
</tr>
<tr>
<td>Length</td>
<td>26 ft</td>
</tr>
<tr>
<td>Capacity</td>
<td>862.76 ft³</td>
</tr>
<tr>
<td>Residence Time</td>
<td>1 min</td>
</tr>
<tr>
<td>Pressure Change</td>
<td>1 psia</td>
</tr>
<tr>
<td>Outlet Total Flow</td>
<td>50,696.94 ft³/hr</td>
</tr>
<tr>
<td>Per Vessel</td>
<td>51,765.59 ft³/hr</td>
</tr>
<tr>
<td>Total Needed</td>
<td>1</td>
</tr>
<tr>
<td>Material</td>
<td>0</td>
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</tbody>
</table>

### Composition

<table>
<thead>
<tr>
<th>Material</th>
<th>Outlet Liquid</th>
<th>Outlet Vapor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

### Materials

<table>
<thead>
<tr>
<th>Stream Number</th>
<th>Inlet</th>
<th>Outlet Liquid</th>
<th>Outlet Vapor</th>
</tr>
</thead>
<tbody>
<tr>
<td>338</td>
<td>210,254.90</td>
<td>191,283.70</td>
<td>18,971.16 lb/hr</td>
</tr>
<tr>
<td></td>
<td>49,890.54</td>
<td>5,041.99</td>
<td>45,654.95 ft³/hr</td>
</tr>
<tr>
<td></td>
<td>70.23</td>
<td>69.8</td>
<td>69.8 °F</td>
</tr>
<tr>
<td></td>
<td>129</td>
<td>128</td>
<td>128 psia</td>
</tr>
<tr>
<td>Phase</td>
<td>Vapor-Liquid</td>
<td>Liquid</td>
<td>Vapor</td>
</tr>
<tr>
<td>Vapor Fraction</td>
<td>0.09</td>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>Liquid Fraction</td>
<td>0.91</td>
<td>1.00</td>
<td>0</td>
</tr>
</tbody>
</table>
## COND-130

**Unit Operation FLASH2**  
**Operation**: Continuous  
**Cost**: $111,646.91

### Design Data

- **Q**: 2.72E+06 Btu/hr  
- **mc**: 906,671.83 lb/hr  
- **dT**: 19.8072 °F  
- **G**: 300,000.00 lb/hr-ft²  
- **Pressure Drop**: 5 psia  
- **Tube-side Velocity**: 5 ft/s  
- **U (Heat coefficient)**: 100 Btu/ft²-hr-°F  
- **Required Surface Area**: 228 270 ft²  
- **Material**: Carbon  
- **Transfer Efficiency**: 95%

### Composition

<table>
<thead>
<tr>
<th></th>
<th>Hot Stream</th>
<th>Cold Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
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<td>1.00</td>
</tr>
<tr>
<td>Ammonia</td>
<td>1.00</td>
<td>0.00</td>
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</tbody>
</table>

### Materials

<table>
<thead>
<tr>
<th></th>
<th>Ammonia (Shell)</th>
<th>Cold Water (Tube)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream Number</td>
<td>340</td>
<td>343</td>
</tr>
<tr>
<td>Flow Rate</td>
<td>6,268.0</td>
<td>6,268.0</td>
</tr>
<tr>
<td>Vapor Fraction</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Temperature</td>
<td>68</td>
<td>65</td>
</tr>
<tr>
<td>Cp</td>
<td>0.52</td>
<td>1</td>
</tr>
<tr>
<td>u</td>
<td>0.0098</td>
<td>0.67</td>
</tr>
<tr>
<td>k</td>
<td>0.2219</td>
<td>0.363</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>0.597</td>
<td>1</td>
</tr>
<tr>
<td>Fouling Factor</td>
<td>0.0005</td>
<td>0.0005</td>
</tr>
</tbody>
</table>

### Tubes

- **16 BWG tubing 3/4-in**
  - **OD**: 0.75 in  
  - **ID**: 0.62 in  
  - **Square Pitch**: 7 in  
  - **T_in**: 719 F  
  - **T_out**: 70 F  
  - **m**: h lb/hr

### Fluid Mechanics Values

- **N_p**: 4.465  
- **N_u**: 183.988  
- **h**: 1292.664 Btu/ft²-hr-°F  
- **1/ha**: 0.011  
- **ha**: 89.598 Btu/ft²-hr-°F
Mass and Energy Balances

The mass and energy balances are provided for each stream. Because the working fluid operates in a closed loop that involves no chemical reaction, the mass balances hold through each unit operation. However, at the guidance of our consultants in corroboration with Professor Fabiano, it is expected that there is an annual working fluid loss of 5% through leakage. Therefore, this deviation in practice should be taken into consideration for maintenance purposes. The entropy of the system grows larger as the process progresses, which is in accordance with the thermodynamic laws. It is interesting to note that although the mass of working fluid and the air stays constant, the volumetric flow rate varies. This is due to the vaporization of the working fluid, with streams having pure liquid, pure vapor, and vapor-liquid phases. The mass and energy balances hold. As observed, operating with Refrigerant 245 would require approximately 3 times the amount of working fluid that is needed with ammonia.

The unit results are presented in Tables 12 and 13, and display the mass and energy balances for each unit operation. Conservation of energy applies around each unit and for the system as a whole. As noted in the following tables, the enthalpy in and out of heat exchanger unit 116 and flash units 326 and 339 are equal to each other. However, for condenser unit 130, pump 132 and expanders 124, 330 and 336 the enthalpy in the streams is not the same as the enthalpy out. The enthalpy difference can be reconciled by the accounting for the heat duty and net work required for each of the units. After doing these calculations, the energy balance around all of the individual units are balanced. The final amount of recoverable power is equal to the sum of the pump and compressor units. These are 1.79 MW and 2.00 MW for ammonia and R245, respectively.

The energy balance for the entire process is also balanced. All of the energy transferred from the original air stream can be found by adding the net work and heat duties of units 124, 130, 132, 330 and 336.
Table 10 shows the mass and energy balances for the various streams in the Low-Grade Heat Recovery Cycle utilizing Ammonia.
Table 11 shows the mass and energy balances for the various streams in the Low-Grade Heat Recovery Cycle utilizing Refrigerant-245.
**Unit Balances**

Table 12 shows the mass and energy balances for the various units in the Low-Grade Heat Recovery Cycle utilizing Ammonia.

<table>
<thead>
<tr>
<th>Property</th>
<th>UNITS</th>
<th>116</th>
<th>116</th>
<th>130</th>
<th>132</th>
<th>326</th>
<th>339</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOLE IN (LBMOL/HR)</td>
<td></td>
<td>87654.3</td>
<td>87654.3</td>
<td>6268.21</td>
<td>17500</td>
<td>17500</td>
<td>12345.7</td>
</tr>
<tr>
<td>MOLE OUT (LBMOL/HR)</td>
<td></td>
<td>87654.3</td>
<td>87654.3</td>
<td>6268.21</td>
<td>17500</td>
<td>17500</td>
<td>12345.7</td>
</tr>
<tr>
<td>MASS IN (LB/HR)</td>
<td></td>
<td>2.27E+06</td>
<td>2.27E+06</td>
<td>106751</td>
<td>298035</td>
<td>298035</td>
<td>210255</td>
</tr>
<tr>
<td>MASS OUT (LB/HR)</td>
<td></td>
<td>2.27E+06</td>
<td>2.27E+06</td>
<td>106751</td>
<td>298035</td>
<td>298035</td>
<td>210255</td>
</tr>
<tr>
<td>ENTHALPY IN (BTU/HR)</td>
<td></td>
<td>-5.42E+08</td>
<td>-5.42E+08</td>
<td>-1.23E+08</td>
<td>-5.09E+08</td>
<td>-4.51E+08</td>
<td>-3.49E+08</td>
</tr>
<tr>
<td>ENTHALPY OUT (BTU/HR)</td>
<td></td>
<td>-5.42E+08</td>
<td>-5.42E+08</td>
<td>-1.82E+08</td>
<td>-5.08E+08</td>
<td>-4.51E+08</td>
<td>-3.49E+08</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Property</th>
<th>UNITS</th>
<th>336</th>
<th>330</th>
<th>124</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOLE IN (LBMOL/HR)</td>
<td></td>
<td>12345.7</td>
<td>5154.26</td>
<td>17500</td>
</tr>
<tr>
<td>MOLE OUT (LBMOL/HR)</td>
<td></td>
<td>12345.7</td>
<td>5154.26</td>
<td>17500</td>
</tr>
<tr>
<td>MASS IN (LB/HR)</td>
<td></td>
<td>210255</td>
<td>87779.9</td>
<td>298035</td>
</tr>
<tr>
<td>MASS OUT (LB/HR)</td>
<td></td>
<td>210255</td>
<td>87779.9</td>
<td>298035</td>
</tr>
<tr>
<td>ENTHALPY IN (BTU/HR)</td>
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<td>-3.49E+08</td>
<td>-9.72E+07</td>
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<tr>
<td>ENTHALPY OUT (BTU/HR)</td>
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<td>-3.49E+08</td>
<td>-1.00E+08</td>
<td>-4.51E+08</td>
</tr>
</tbody>
</table>

130 - Heat Duty | 5.96E+07 BTU/HR = 17474.79 KW
132 - Net Work  | -1.40E+06 BTU/HR = -411.20 KW
336 - Net Work  | 4.37E+05 BTU/HR = 128.08 KW
330 - Net Work  | 3.16E+06 BTU/HR = 925.32 KW
124 - Net Work  | 3.92E+06 BTU/HR = 1148.59 KW

**Total Net Work** | **1790.80 KW**
Table 13 shows the mass and energy balances for the various units in the Low-Grade Heat Recovery Cycle utilizing Refrigerant-245.

<table>
<thead>
<tr>
<th>Property</th>
<th>UNITS</th>
<th>116</th>
<th>116</th>
<th>130</th>
<th>132</th>
<th>326</th>
<th>339</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOLE IN (LBMOL/HR)</td>
<td></td>
<td>76183.9</td>
<td>76183.9</td>
<td>5671.42</td>
<td>7000</td>
<td>7000</td>
<td>2816.06</td>
</tr>
<tr>
<td>MOLE OUT (LBMOL/HR)</td>
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<td>76183.9</td>
<td>76183.9</td>
<td>5671.42</td>
<td>7000</td>
<td>7000</td>
<td>2816.06</td>
</tr>
<tr>
<td>MASS IN (LB/HR)</td>
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<td>3.38E+06</td>
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<td>938342</td>
<td>377489</td>
</tr>
<tr>
<td>MASS OUT (LB/HR)</td>
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<td>3.38E+06</td>
<td>3.38E+06</td>
<td>760247</td>
<td>938342</td>
<td>938342</td>
<td>377489</td>
</tr>
<tr>
<td>ENTHALPY IN (BTU/HR)</td>
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<td>-5.33E+09</td>
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<td>-1.36E+09</td>
</tr>
<tr>
<td>ENTHALPY OUT (BTU/HR)</td>
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<td>-5.33E+09</td>
<td>-5.33E+09</td>
<td>-2.76E+09</td>
<td>-3.40E+09</td>
<td>-3.35E+09</td>
<td>-1.36E+09</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Property</th>
<th>UNITS</th>
<th>336</th>
<th>330</th>
<th>124</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOLE IN (LBMOL/HR)</td>
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<td>2816.06</td>
<td>4183.94</td>
<td>7000</td>
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<tr>
<td>MOLE OUT (LBMOL/HR)</td>
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<td>4183.94</td>
<td>7000</td>
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<tr>
<td>MASS IN (LB/HR)</td>
<td></td>
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<td>560853</td>
<td>938342</td>
</tr>
<tr>
<td>MASS OUT (LB/HR)</td>
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<td>377489</td>
<td>560853</td>
<td>938342</td>
</tr>
<tr>
<td>ENTHALPY IN (BTU/HR)</td>
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<td>-1.36E+09</td>
<td>-1.98E+09</td>
<td>-3.35E+09</td>
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<tr>
<td>ENTHALPY OUT (BTU/HR)</td>
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<td>-1.36E+09</td>
<td>-1.99E+09</td>
<td>-3.35E+09</td>
</tr>
</tbody>
</table>

130 - Heat Duty | 5.88E+07 BTU/HR = 17224.50 KW
132 - Net Work  | -1.29E+06 BTU/HR = -378.08 KW
336 - Net Work  | 1.13E+06 BTU/HR = 331.18 KW
330 - Net Work  | 5.50E+06 BTU/HR = 1611.96 KW
124 - Net Work  | 1.51E+06 BTU/HR = 442.56 KW

Total Net Work | 2007.62 KW
Economic Analysis

Overview

Discounted cash flow analysis (DCF) was used to estimate the value of this project over its twenty-year lifespan. This valuation was compared to the initial capital expenditure in order to determine if the project would be worthwhile to undertake. Sensitivity analysis was used to show financial return as a function of several key factors in the process, such as expander costs and electricity prices.

Sales

All revenue for this process is derived from the sale of electricity. The power generated is 2.2MW, which translates into a maximum electricity production of 17,424,000kW-hr per year. The average retail price of electricity in the United States in 2009 was $0.0989 per kW-hr. However, the retail price is after taxes and surcharges. At the suggestion of consultant Mr. John Wismer, a retail price for electricity of $0.08 per kW-hr is used, which calculates into total revenue of $1.39MM per year.

Over the lifetime of this process, electricity prices are projected to rapidly decrease in the next ten five years and then slowly increase back to parity by 2030 as shown in Figure 13 from the U.S. Energy Information Administration (EIA). Therefore, we decreased the sale price of electricity proportionally from $0.08 following EIA’s projections using 2008 as the base year. The cost of electricity was projected to go up at an annual rate of 0.67%. Annual cash flows reflect adjusted electricity sale prices in the discounted cash flow model.
Figure 13 shows energy prices from 1980-2035 in terms of 2008 dollars per million Btu. (Source: EIA, 2010)

**Cost Assessment**

**Capital Investment**

The capital investment requirement was calculated using a combination of correlations and equations in addition to price quotes from companies. All these equipment costs are then multiplied by their respective bare-modulus factors as outlined in Seider et al. in order to account for installation, piping, contingencies, etc. The cost of each piece of equipment along with their bare-modulus factors are shown in Table 14.

In addition to all the capital equipment, the cost of ammonia to fill the total process initially must be accounted for. The entire volume of the process is calculated to be 287m$^3$, which is equivalent to 195.92 metric tons of ammonia. The price of ammonia used is the spring 2010 price of $365 per metric ton cost and freight (CFR) delivered to Tampa (ICIS Heren, 2010). Therefore, the total cost of ammonia is $71,512.08.

Costs for site preparations and service facilities were taken to each be 5.0% of total bare module costs. Total direct permanent investment is the sum of total bare module costs and the costs of site preparation and service facilities. Contingencies and contractor fees were taken to be 18.0% of direct permanent investment. The sum of these fees and direct permanent investment yielded total
depreciable capital. The cost of land and royalties is taken to be zero because the process will be built attached to existing equipment. The cost of plant start up is 10.0% of the total depreciable capital.

The sum of all of these costs lead to a Total Permanent Investment of $6,521,003. The salvage value at the end of the twenty year process is assumed to be nothing.
<table>
<thead>
<tr>
<th>Item No.</th>
<th>Equipment</th>
<th>( C_p )</th>
<th>Quantity</th>
<th>Bare-Module Factor</th>
<th>Cost of Bare Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>HX-116</td>
<td>Plate and Fin Heat Exchanger</td>
<td>$236,272.90</td>
<td>3</td>
<td>2.17</td>
<td>$985,257.99</td>
</tr>
<tr>
<td>COND-130</td>
<td>Cold Water Shell and Tube Heat Exchanger</td>
<td>$111,647.00</td>
<td>1</td>
<td>3.18</td>
<td>$355,037.46</td>
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<tr>
<td>EXP-124</td>
<td>Liquid Expander</td>
<td>$238,447.40</td>
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<td>1.50</td>
<td>$357,671.10</td>
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<tr>
<td>EXP-336</td>
<td>Liquid Expander</td>
<td>$51,370.65</td>
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<td>1.50</td>
<td>$77,055.98</td>
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<tr>
<td>EXP-330</td>
<td>Vapor Expander</td>
<td>$169,900.30</td>
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<td>2.34</td>
<td>$397,566.70</td>
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<tr>
<td>PUMP-132</td>
<td>Ammonia Compressor</td>
<td>$165,123.10</td>
<td>2</td>
<td>3.30</td>
<td>$1,089,812.46</td>
</tr>
<tr>
<td>Not Shown</td>
<td>Cooling Tower</td>
<td>$550,000.00</td>
<td>1</td>
<td>2.04</td>
<td>$1,122,000.00</td>
</tr>
<tr>
<td>FLASH-326</td>
<td>Initial Flash Vessel</td>
<td>$173,482.90</td>
<td>1</td>
<td>4.16</td>
<td>$721,688.86</td>
</tr>
<tr>
<td>FLASH-339</td>
<td>Secondary Flash Vessel</td>
<td>$92,649.13</td>
<td>1</td>
<td>4.16</td>
<td>$385,420.38</td>
</tr>
</tbody>
</table>

Table 14 shows the unit costs, bare-module calibration factors as specified by Seider et al, and bare module costs.
Variable Costs

The direct variable costs that are incurred are utilities, which can be broken down into electricity and cooling water consumption. This process requires electricity to power the pump that circulates the ammonia working fluid. Electricity consumption is 411kW, which translates into 3.26MM kW-hr per year. However, instead of purchasing power to operate the pump, the electricity requirement is subtracted from the total electricity produced to arrive at a net power generation of 1.8MW. In addition to electricity, this modified Rankine cycle requires cooling water in order to liquefy the ammonia. Following the advice of Dr. Shieh, the cooling power will be created by evaporating water. Therefore, the cooling utility cost is equal to the cost of makeup water required. Following the guidelines in Seider et al, the cost of cooling water is $0.01 per 1000 gallons.

Fixed Costs

The two fixed costs for the process are maintenance and repair of the equipment, and working fluid makeup due to loss. They are determined using the method described in Seider et al.

Maintenance costs include maintenance and repair of the equipment. Annual maintenance wages and benefits (MW&B) for a fluids handling process is calculated as 3.5% of the cost of total depreciable capital (TDC). Salaries and benefits, materials and services, and maintenance overhead are charged at 25%, 100% and 5% of MW&B, respectively. The annual maintenance cost is $561,434.

At the advice of Mr. John Wismer, cost of operators and managers are taken to be zero because we can utilize the operators and managers that are already hired for the process from which the heat source originates. In addition, operating overhead was taken to be zero because those costs would be incorporated into the plant operations and not the operations of this specific process.

Inflation and Price Level

Following general valuation standards, general inflation is ignored in the analysis (Koller, Goedhart, & Wessels, 2005). Therefore, inflation is ignored when calculating the cash flows of future years and in discounting them to present value. However, inflation is factored into two parts of the economic analysis. First, the weighted average cost of capital as discussed later contains inflation. The risk free rate used is the notional value and not real interest rates because inflation is part of the cost of money over time and therefore must be discounted in order to find net present values. Second, inflation is included into the cost of electricity because rising energy prices are a significant factor in the sales values, and their inclusion into our model were discussed in the previous section.
Other Economic Costs and Considerations

Aside from the costs calculated, there are several costs not factored into the direct costs but must be considered as well. The largest of these costs are legal and environmental contingencies because the working fluid that is used is ammonia under high pressure. Although ammonia is regulated as a non-flammable gas in the United States, it meets the definitions of a material that is toxic by inhalation. Exposure to high levels of ammonia causes irritation and serious burns on the skin and in the mouth, throat, lungs and eyes (Center for Disease Control, 2004).

Although humans and other mammals are able to convert ammonia into carbamoyl phosphate in the body and then excrete it in urine, fish and amphibians lack this mechanism. Therefore, ammonia is classified as dangerous for the environment because even dilute concentrations of it is highly toxic to aquatic animals.

If a valve, pipe or process unit fails and the plant experiences major ammonia leaks, then the company is liable for environmental cleanup fees and penalties from the government and Environmental Protection Agency (EPA). In addition, the company is liable for legal fees and costs of large settlement due to lawsuits from the government and community.

Valuation

In order to value this project, several key ratios have to be calculated such as effective tax rate and cost of capital. Therefore, the first step in the valuation process is determining the industry that this process will be used in, and then selecting relevant companies.

Comparable Companies

The low-grade heat recovery process is most pertinent to the power generation industry. Therefore, six companies in this industry were selected. The only requirement are that the companies were public in order for information to be readily available from 10-K filings.

The six companies selected are Southern Co (SO), Constellation Energy (CEG), Exelon Corp (EXC), AES Corp (AES), First Energy Corp (FE) and NRG Energy, Inc (NRG). In order to find a representative cross section of the entire industry, an attempt is made to select companies that are different in size, location, and power generation method. For example, the largest company is Constellation Energy with an enterprise value of close to $80B, while the smallest company is NRG with an enterprise value of only $11B. Southern
Co derives over 70% of its power generation from coal, while Exelon almost exclusively uses nuclear power. Detailed information for each of these six firms is provided in Table 15.

Table 15 shows detailed 2009 information on the basket of six companies used for calculating valuation ratios (Source: Bloomberg)

<table>
<thead>
<tr>
<th>Company</th>
<th>Adj Beta</th>
<th>Raw Beta</th>
<th>Debt/Equity</th>
<th>Pretax Income</th>
<th>Income Tax Expense</th>
<th>Tax Rate</th>
<th>Unlevered Betas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern Co (SO)</td>
<td>0.568</td>
<td>0.352</td>
<td>135.69%</td>
<td>$2,608.00</td>
<td>$898.00</td>
<td>34.43%</td>
<td>0.301</td>
</tr>
<tr>
<td>Constellation Energy (CEG)</td>
<td>0.755</td>
<td>0.633</td>
<td>161.37%</td>
<td>$1,263.90</td>
<td>$428.30</td>
<td>33.89%</td>
<td>0.365</td>
</tr>
<tr>
<td>Exelon Corp (EXC)</td>
<td>0.925</td>
<td>0.888</td>
<td>99.64%</td>
<td>$4,418.00</td>
<td>$1,712.00</td>
<td>38.75%</td>
<td>0.574</td>
</tr>
<tr>
<td>AES Corp (AES)</td>
<td>1.183</td>
<td>1.274</td>
<td>428.98%</td>
<td>$2,784.00</td>
<td>$774.00</td>
<td>27.80%</td>
<td>0.289</td>
</tr>
<tr>
<td>First Energy Corp (FE)</td>
<td>0.803</td>
<td>0.704</td>
<td>174.35%</td>
<td>$2,119.00</td>
<td>$777.00</td>
<td>36.67%</td>
<td>0.382</td>
</tr>
<tr>
<td>NRG (NRG)</td>
<td>1.266</td>
<td>1.178</td>
<td>118.24%</td>
<td>$1,729.00</td>
<td>$713.00</td>
<td>41.24%</td>
<td>0.747</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>186.38%</td>
<td></td>
<td></td>
<td>35.46%</td>
<td>0.443</td>
</tr>
</tbody>
</table>

**Determining Effective Tax Rate**

The tax rate is an important part of the process in determining net income, which flows into cash flows, as well as in determining the size of the depreciation tax shield. Although KPMG reports the tax rate in the United States at 40% for corporations (KPMG, 2009), the effective marginal tax rate is in fact lower due to various write offs and tax benefits.

The effective rate, found by averaging the effective tax rate of the basket of utility companies, is actually only 35.46%. The effective tax rate of each individual company is determined by diving the income tax expensive by their pretax incomes on their annual Income Statements, and then averaging these values for the previous five years.

**Calculating the Weighted-Average Cost of Capital (WACC)**

The weighted-average cost of capital is used to discount cash flows because companies have access to two sources of funding, equity and debt. Therefore, the required return by a firm is a mixture of these two sources of funding. Historically, the cost of equity, $r_e$, is higher than the cost of debt, $r_d$, at around 20% compared to 5% respectively. AA rated companies typically only have to pay one hundred fifty basis points above treasuries to borrow, which makes debt a cheap source of funding. In addition, debt has the added
benefit that interest payments serve as tax shields, which reduces the amount of taxes a corporation has to pay.

The equation for WACC is shown below, where E and D are the market values of the firm’s equity and debt, respectively, V is the sum of E and D, and TC is the corporate tax rate.

\[
WACC = \frac{E}{V} r_e + \frac{D}{V} r_d (1 - T_c)
\]  

(Eq. 2)

Calculating the cost of debt requires finding the debt rating given to the firm by Moody’s, Fitch or Standard & Poor’s, and then finding the premium that a firm with that type of rating would pay to borrow money.

Calculating the cost of equity is a much more difficult and involved process that requires using the Capital Asset Pricing Model (CAPM) below. Beta is the levered average beta of the basket of companies, rm is the returns of the market, and rf is the returns of the one year Treasury bill.

\[
r_e = \beta_{L,Avg} (r_m - r_f) + rf
\]  

(Eq. 3)

First, the individual beta values, BL, of a basket of companies are calculated by finding the slope of linear regression of the each company’s returns against the returns of the market. Then the beta is unlevered by each company’s debt structure in the following equation to find the unlevered beta, BU.

\[
\beta_u = \frac{\beta_L}{1 + (1 - T_C)(D/E)}
\]  

(Eq. 4)

Then, the beta is averaged to find a basket average beta, which is re-levered to find BL using the equation above by using the average corporate tax rate and the average debt to equity ratios of the basket.

The average levered beta calculated using the average debt to equity ratio and average tax rate of the basket of companies is 0.09757. Using the CAPM and an expected market risk premium of 5% and risk free rate of 4.5% as stated in Koller et al., the expected return on equity is 9.38%. Using the WACC with the
cost of debt for an AA company of 150 basis points above treasuries, the cost of capital for this project was calculated to be 5.79%.

Although this figure appears conservative, it must be taken under consideration that most utility companies are levered at least two-thirds debt, which is much cheaper than equity. In addition, the risk, also known as the beta, of utilities is lower than traditional chemical and industrial companies are because their business models are different. Whereas most companies’ sales depend on macroeconomic trends such as economic expansion or recession, utilities have much more stable sales and cash flows because electricity is a staple for both consumers and producers. This is why utilities are labeled as a defensive or non-cyclical industry.

**Discounted Cash Flow Analysis**

After calculating the WACC and effective corporate tax rates, the discounted cash flow model can be built. The revenue and cost of the process is projected over the life of the equipment, in this case twenty years. For each year, the difference between revenue and cost is the process’ operating earnings before interest, taxes, depreciation and amortization (EBITDA). Depreciation expenses the cost of the capital cost of the equipment over twenty years using the modified accelerated cost recovery system (MACRS) as defined by FASB, and is subtracted from EBITDA to arrive at earnings before interest and taxes (EBIT).

Taxes (the rate was determined earlier) are then subtracted from EBIT to arrive at the beginning of the cash flow statement. To after-taxes EBIT, depreciation is added back while capital expenses are subtracted in order to arrive at the year’s cash flow. It is assumed there is no amortization or changes in operating working capital for this process.

Each year’s cash flow is discounted using the following equation and then summed to arrive at the net present value of the process.
At the end of twenty years of operation, there is assumed to be no salvage value in the equipment.

In addition, as detailed in Seider et al., plant operation as the equipment is installed and optimized.

Therefore, the full capacity of the plant it was assumed that the installation is completed over two years at a linear rate. Therefore, the process is not cash flow positive until year three.
Table 16 shows the annual variable cost summary of the Low-Grade Heat Recovery Cycle.

<table>
<thead>
<tr>
<th>Variable Costs at 100% Capacity:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General Expenses</strong></td>
<td></td>
</tr>
<tr>
<td>Selling / Transfer Expenses:</td>
<td>$</td>
</tr>
<tr>
<td>Direct Research:</td>
<td>$</td>
</tr>
<tr>
<td>Allocated Research:</td>
<td>$</td>
</tr>
<tr>
<td>Administrative Expense:</td>
<td>$</td>
</tr>
<tr>
<td>Management Incentive Compensation:</td>
<td>$</td>
</tr>
<tr>
<td><strong>Total General Expenses</strong></td>
<td>$</td>
</tr>
<tr>
<td><strong>Raw Materials</strong></td>
<td>$0</td>
</tr>
<tr>
<td><strong>Byproducts</strong></td>
<td>$0</td>
</tr>
<tr>
<td><strong>Utilities</strong></td>
<td>$347,378</td>
</tr>
<tr>
<td><strong>Total Variable Costs</strong></td>
<td>$347,378</td>
</tr>
</tbody>
</table>
Table 17 shows the annual fixed cost summary of the Low-Grade Heat Recovery Cycle.

<table>
<thead>
<tr>
<th>Fixed Cost Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operations</strong></td>
</tr>
<tr>
<td>Direct Wages and Benefits</td>
</tr>
<tr>
<td>Direct Salaries and Benefits</td>
</tr>
<tr>
<td>Operating Supplies and Services</td>
</tr>
<tr>
<td>Technical Assistance to Manufacturing</td>
</tr>
<tr>
<td>Control Laboratory</td>
</tr>
<tr>
<td><strong>Total Operations</strong></td>
</tr>
<tr>
<td><strong>Maintenance</strong></td>
</tr>
<tr>
<td>Wages and Benefits</td>
</tr>
<tr>
<td>Salaries and Benefits</td>
</tr>
<tr>
<td>Materials and Services</td>
</tr>
<tr>
<td>Maintenance Overhead</td>
</tr>
<tr>
<td><strong>Total Maintenance</strong></td>
</tr>
<tr>
<td><strong>Operating Overhead</strong></td>
</tr>
<tr>
<td>General Plant Overhead:</td>
</tr>
<tr>
<td>Mechanical Department Services:</td>
</tr>
<tr>
<td>Employee Relations Department</td>
</tr>
<tr>
<td>Business Services:</td>
</tr>
<tr>
<td><strong>Total Operating Overhead</strong></td>
</tr>
<tr>
<td><strong>Property Taxes and Insurance</strong></td>
</tr>
<tr>
<td>Property Taxes and Insurance:</td>
</tr>
<tr>
<td><strong>Other Annual Expenses</strong></td>
</tr>
<tr>
<td>Rental Fees (Office and Laboratory Space):</td>
</tr>
<tr>
<td>Licensing Fees:</td>
</tr>
<tr>
<td>Miscellaneous:</td>
</tr>
<tr>
<td><strong>Total Other Annual Expenses</strong></td>
</tr>
<tr>
<td><strong>Total Fixed Costs</strong></td>
</tr>
</tbody>
</table>
Table 18 shows the investment summary of the Low-Grade Heat Recovery Cycle.

### Investment Summary

<table>
<thead>
<tr>
<th>Bare Module Costs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabricated Equipment</td>
<td>$ -</td>
</tr>
<tr>
<td>Process Machinery</td>
<td>$4,198,421</td>
</tr>
<tr>
<td>Spares</td>
<td>$ 544,906</td>
</tr>
<tr>
<td>Storage</td>
<td>$ 558,300</td>
</tr>
<tr>
<td>Other Equipment</td>
<td>$ -</td>
</tr>
<tr>
<td>Materials</td>
<td>$ 71,512</td>
</tr>
<tr>
<td>Computers, Software, Etc.</td>
<td>$ -</td>
</tr>
<tr>
<td><strong>Total Bare Module Costs</strong></td>
<td><strong>$ 5,373,139</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Direct Permanent Investment</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of Site Preparations</td>
<td>$ 268,657</td>
</tr>
<tr>
<td>Cost of Service Facilities</td>
<td>$ 268,657</td>
</tr>
<tr>
<td>Allocated Costs for utility plants and related facilities</td>
<td>$ -</td>
</tr>
<tr>
<td><strong>Direct Permanent Investment</strong></td>
<td><strong>$ 5,910,453</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Depreciable Capital</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of Contingencies &amp; Contractor Fees</td>
<td>$ 1,063,882</td>
</tr>
<tr>
<td><strong>Total Depreciable Capital</strong></td>
<td><strong>$ 6,974,335</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Permanent Investment</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of Land</td>
<td>$ -</td>
</tr>
<tr>
<td>Cost of Royalties</td>
<td>$ -</td>
</tr>
<tr>
<td>Cost of Plant Start-Up</td>
<td>$ 697,433</td>
</tr>
<tr>
<td><strong>Total Permanent Investment - Unadjusted</strong></td>
<td><strong>$ 7,671,768</strong></td>
</tr>
<tr>
<td>Site Factor</td>
<td>0.85</td>
</tr>
<tr>
<td><strong>Total Permanent Investment</strong></td>
<td><strong>$ 6,521,003</strong></td>
</tr>
</tbody>
</table>
### Cash Flow Summary

<table>
<thead>
<tr>
<th>Year</th>
<th>Percentage of Design Capacity</th>
<th>Price</th>
<th>Sales</th>
<th>Capital Costs</th>
<th>Working Capital</th>
<th>Var Costs</th>
<th>Fixed Costs</th>
<th>Depreciation</th>
<th>Depletion Allowance</th>
<th>Taxable Income</th>
<th>Taxes</th>
<th>Net Earnings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>0%</td>
<td>$0.08</td>
<td>1,393,900</td>
<td>-</td>
<td>(3,260,500)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2012</td>
<td>0%</td>
<td>$0.08</td>
<td>1,403,300</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2013</td>
<td>100%</td>
<td>$0.08</td>
<td>1,412,700</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(261,500)</td>
<td>-</td>
<td>84,100</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
<tr>
<td>2014</td>
<td>100%</td>
<td>$0.08</td>
<td>1,422,100</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(503,500)</td>
<td>-</td>
<td>(148,500)</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
<tr>
<td>2015</td>
<td>100%</td>
<td>$0.08</td>
<td>1,431,700</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(465,700)</td>
<td>-</td>
<td>(101,300)</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
<tr>
<td>2016</td>
<td>100%</td>
<td>$0.08</td>
<td>1,441,200</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(430,800)</td>
<td>-</td>
<td>(57,000)</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
<tr>
<td>2017</td>
<td>100%</td>
<td>$0.08</td>
<td>1,450,800</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(503,500)</td>
<td>-</td>
<td>(148,500)</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
<tr>
<td>2018</td>
<td>100%</td>
<td>$0.08</td>
<td>1,460,400</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(465,700)</td>
<td>-</td>
<td>(101,300)</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
<tr>
<td>2019</td>
<td>100%</td>
<td>$0.08</td>
<td>1,470,000</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(430,800)</td>
<td>-</td>
<td>(57,000)</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
<tr>
<td>2020</td>
<td>100%</td>
<td>$0.08</td>
<td>1,479,600</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(398,400)</td>
<td>-</td>
<td>(15,100)</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
<tr>
<td>2021</td>
<td>100%</td>
<td>$0.08</td>
<td>1,489,200</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(368,600)</td>
<td>-</td>
<td>(15,100)</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
<tr>
<td>2022</td>
<td>100%</td>
<td>$0.08</td>
<td>1,498,800</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(340,900)</td>
<td>-</td>
<td>(15,100)</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
<tr>
<td>2023</td>
<td>100%</td>
<td>$0.08</td>
<td>1,508,400</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(311,200)</td>
<td>-</td>
<td>(15,100)</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
<tr>
<td>2024</td>
<td>100%</td>
<td>$0.08</td>
<td>1,518,000</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(281,500)</td>
<td>-</td>
<td>(15,100)</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
<tr>
<td>2025</td>
<td>100%</td>
<td>$0.08</td>
<td>1,527,600</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(251,800)</td>
<td>-</td>
<td>(15,100)</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
<tr>
<td>2026</td>
<td>100%</td>
<td>$0.08</td>
<td>1,537,200</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(222,100)</td>
<td>-</td>
<td>(15,100)</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
<tr>
<td>2027</td>
<td>100%</td>
<td>$0.08</td>
<td>1,546,800</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(192,400)</td>
<td>-</td>
<td>(15,100)</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
<tr>
<td>2028</td>
<td>100%</td>
<td>$0.08</td>
<td>1,556,400</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(162,700)</td>
<td>-</td>
<td>(15,100)</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
<tr>
<td>2029</td>
<td>100%</td>
<td>$0.08</td>
<td>1,566,000</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(133,000)</td>
<td>-</td>
<td>(15,100)</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
<tr>
<td>2030</td>
<td>100%</td>
<td>$0.08</td>
<td>1,575,600</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(103,300)</td>
<td>-</td>
<td>(15,100)</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
<tr>
<td>2031</td>
<td>100%</td>
<td>$0.08</td>
<td>1,585,200</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(73,600)</td>
<td>-</td>
<td>(15,100)</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
<tr>
<td>2032</td>
<td>100%</td>
<td>$0.09</td>
<td>1,594,800</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(43,900)</td>
<td>-</td>
<td>(15,100)</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
<tr>
<td>2033</td>
<td>100%</td>
<td>$0.09</td>
<td>1,604,400</td>
<td>-</td>
<td>(347,400)</td>
<td>(700,900)</td>
<td>(155,600)</td>
<td>-</td>
<td>(15,100)</td>
<td>52,700</td>
<td>35,900</td>
<td>54,300</td>
</tr>
</tbody>
</table>

Table 19 shows the discounted cash flow (DCF) analysis of the heat recovery cycle process.
Profitability Analysis

At an electricity sale price of $0.08 per kW-hr and total permanent investment of $6,521,003, the process generates a positive internal rate of return (IRR) of 2.32%. The net present value of the 20-year process is -$1,857,800. Even though the IRR is positive, the net present value of the project is negative because the cost of capital is 5.79%, which is greater than the IRR.

Table 20 shows a sensitivity analysis for our process as the total permanent investment changes by increments of ±10% and as the price of electricity changes in increments of ±10%. The values in green represent a positive IRR, whereas values in red represent a negative IRR. Figure 14 shows Table 20 in graphical form. In order for the project to have a positive net present value, the internal rate of return must be greater than the cost of capital. Therefore, the price of electricity must increase by 20% to $0.096 per kW-hr in order for the project to generate an IRR greater than WACC. However, if 10% of the total permanent investment cost can be cut, then the project would be very close to positive net present value without requiring an increase in the price of electricity.

The best way to improve the project is to cut down on annual fixed costs or total permanent investment because the price of electricity moves very slowly due to the regulation of the utilities industry by the United States government.

Table 20 shows the sensitivity analysis for returns on the heat recovery cycle as a function of changing total permanent investment and electricity prices.

<table>
<thead>
<tr>
<th>Product Price</th>
<th>Total Permanent Investment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$3,260,501</td>
</tr>
<tr>
<td>$0.0400</td>
<td>1.21%</td>
</tr>
<tr>
<td>$0.0480</td>
<td>8.58%</td>
</tr>
<tr>
<td>$0.0560</td>
<td>14.46%</td>
</tr>
<tr>
<td>$0.0640</td>
<td>19.54%</td>
</tr>
<tr>
<td>$0.0720</td>
<td>24.24%</td>
</tr>
<tr>
<td>$0.0800</td>
<td>28.08%</td>
</tr>
<tr>
<td>$0.0880</td>
<td>32.93%</td>
</tr>
<tr>
<td>$0.0960</td>
<td>37.04%</td>
</tr>
<tr>
<td>$0.1040</td>
<td>41.01%</td>
</tr>
<tr>
<td>$0.1120</td>
<td>44.88%</td>
</tr>
<tr>
<td>$0.1200</td>
<td>48.62%</td>
</tr>
</tbody>
</table>
Figure 14 shows various different total permanent investment costs are graphed against changes in the price of electricity to show the IRR.
Other Important Considerations

Plant Safety

The majority of the streams in the process are composed of the working fluid. The various working fluids may potentially be explosive in air. Concerns about leaks should be exercised at relatively high temperatures when auto ignition may be possible. These high working fluid temperatures may lead to an explosion. Although none of the working fluids approach auto ignition temperatures, caution should be taken for the sections of the plant with the highest temperatures. There should be an effort to minimize risk for flames or sparks in the plant. Emergency shut off valves should be installed to meet safety standards. In addition, the streams are at high temperatures and physical contact should be avoided.

Some of the units need to be designed specifically for higher pressures. These units need to be monitored and specially controlled as to avoid leaks.

Environmental Considerations

All of the refrigerants pose some threat to the environment. The following Table 21 lists the toxicities, ozone risks and global warming associated with each of the working fluids (IHS, 2010).

Table 21 shows the environmental and health safety risks of the various refrigerants.

<table>
<thead>
<tr>
<th>Refrigerant Name</th>
<th>Toxicity at Proposed Levels</th>
<th>Ozone Risk</th>
<th>Global Warming Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>R134a</td>
<td>Non-Toxic</td>
<td>Negligible</td>
<td>Significant</td>
</tr>
<tr>
<td>R245</td>
<td>Non-Toxic</td>
<td>Negligible</td>
<td>Significant</td>
</tr>
<tr>
<td>Propane</td>
<td>Non-Toxic</td>
<td>Negligible</td>
<td>Negligible</td>
</tr>
<tr>
<td>Pentane</td>
<td>Non-Toxic</td>
<td>Negligible</td>
<td>Negligible</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>Non-Toxic</td>
<td>Negligible</td>
<td>Negligible</td>
</tr>
<tr>
<td>Ammonia</td>
<td>Toxic</td>
<td>Negligible</td>
<td>Negligible</td>
</tr>
</tbody>
</table>

The cooling water utilities only increase the temperature of water by 3°F, which is an acceptable temperature change for this process. This small difference likely will not cause change to the ecosystem of the water source.

Plant Control

The feed air stream is set at a feed rate of 65000 lb-mol/hr. In a real plant, this feed rate may fluctuate based on the conditions of the process or where the air stream is coming from. The air stream can be lower than the expected amount without safety repercussions; it just means that the thermodynamics of the cycle will not be as efficient. If this feed stream is greater than the set feed rate, it may cause a large increase in the temperature of the working fluid in the modified Rankine cycle. Such an increase would increase the likelihood of the previously mentioned auto ignition of the working fluid in the system. To
alleviate this concern, a flow controller should be implemented for the air stream. The closed refrigerant system should not be too much of a concern for flow buildup.

However, control systems should be added after the pump 132 to ensure no significant change in flow. Pump 132 must also have more casing protection relative to the other process units because of the high pressures involved.

To economize the amount of cooling water needed, a cooling water controller system can be utilized. The amount of cooling water needed can be controlled indirectly by monitoring the inlet vapor pressure of the condenser which affects the amount of vapor condensed. We expect that the response of this system will be rather slow. A Proportional Integral controller will make it even slower and if we attempted to use high gains to speed up the response, we may get a system with undesirable, highly oscillatory response. Therefore, a Proportional Integral Derivative controller should be selected because it will provide enough speed and robustness.
Conclusions and Recommendations

The modified Organic Rankine Cycle is used to recover useful work, in this case electricity, from low-grade heat sources. From a hot stream of 65,000lb-mol per hour air at 120psi and 230°F, 1.8MW of electricity can be recovered. Currently, this heat source is being dumped into a cold sink and then released into the environment. However, as energy consumption increases in the world with the recent explosion in demand from Brazil, Russia, India and China, marginal electricity sources will become more important because of increasing demand for limited amount of energy sources used in the generation of electricity. For example, the price of oil hit an all-time high of over $150 per barrel in 2007 (Bloomberg L.P., 2010). In addition, with the dramatic increase in greenhouse gases and pollution in the environment over the past century, preservation of the environment will become more important. Dirty air and water reduces the quality of life for everyone and increases the number of lung and heart disease cases in the world. Therefore, this process has positive social externalities by reducing the amount of power required from power plants, majorities of which are currently coal fired in the world. The burning of coal releases not only carbon dioxide but also sulfates, nitrates and heavy metals such as mercury, lead and cadmium.

At the current average electricity price of $0.08 per kW-hr in the United States, the modified Organic Rankine Cycle generates a positive internal rate of return of 2.32%. The net present value of this 20-year lifespan process is -$1,857,800 because the cost of capital is 5.79%. However, if electricity prices were to increase 17.38% to $0.0939 per kW-hr, then this process would generate an IRR of 5.80%, which is greater than the cost of capital, and would lead to a positive net present value for the project. However, this is assuming that the company that uses this process is in the utilities industry. If the company is in the chemical manufacturing industry, such as Air Products & Chemicals is, then the weighted average cost of capital increases to 10.25%. Electricity prices would have to increase by 44.25% to $0.1154 per kW-hr in order for the process to generate a positive return. Figure 15 shows the cost of capital (WACC) and the required electricity price of electricity in order for the improved Rankine cycle to break even for three potential industries that could use this process.
Figure 15 shows the cost of capital (blue – read on the right axis) of various industries that could utilize the modified Rankine cycle. The red bars (read on the left axis) show the required price of electricity in order for the process to break even. Current cost of electricity (2009) is on average $0.08 per kW-hr in the United States.

Therefore, the design team recommends that management retain the design of this process because it is believed that in the near future, the prices of soaring energy will eventually increase the cost of electricity and therefore make this process attractive financially. With the increase in government subsidies and tax credits for clean energy generation methods, it is advisable that management explore the potential benefits that would be provided to the company from external sources for implementing the modified Organic Rankine Cycle. If the corporation is able to secure government aid for implementing this process, management may find this project more attractive than currently presented without government factors.

At this time however, our conclusion is that although the process is thermodynamically feasible, at the current prices of electricity and the capital costs for the equipment, the process is not economically feasible.
Acknowledgements

Our group would like to thank primarily Mr. Adam Brostow for creating the problem statement and aiding us in the design of its solution, by providing us with valuable advice and working models.

Second, we would like to thank Dr. Wen Shieh for being our faculty advisor and offering his knowledge and expertise in energy extraction and recovery, as well as advising us in the best path to our solution.

Third, we would like to thank Professor Leonard Fabiano for his aid in the design of our ASPEN model and heat exchangers. We appreciate his time and patience, as we needed his help for several hours with our models.

Lastly, this group would like thank all of the consultants that took time to come in every Tuesday afternoon to meet with us in order to help guide us to our solution.
References


Grebenkov, A., Tsurbelev, V., Beliaeva, O., & Timofeyev, B. (n.d.). Experimental Study of Thermodynamic Properties of R245fa.


IHS. (2010). *Ozone Depletion and Global Warming*.


Appendix I: Problem Statement

5. Low-grade Heat Recovery from a Hot Compressor Discharge Stream with Lost Work Analysis
(recommended by Adam A. Brostow, LNG Process Tech., Air Products and Chemicals)

“Uncommon men require no common trust; give him but the scope and he will set the bounds.” – Friedrich von Schiller

Introduction

Energy efficiency is an important issue due to, among other factors, environmental regulations limiting CO2 emissions. Most of the electrical energy supplied by the grid originates with the burning of fossil fuels.

There is an increased incentive to recover heat from relatively low-temperature sources (so-called low-grade or waste heat) and convert it to power. Low-grade heat sources may include hot compressor discharge, hot automobile exhaust, hot streams leaving a chemical reactor, hot geothermal springs, other sources of renewable energy, etc. Most of this heat is wasted because there is no economical way to convert it to power.

Background Information

Figure 1 shows a basic Rankine power cycle. The low-temperature hot stream heats the working fluid in the heat-recovery heat exchanger (HRHX). The working fluid is pumped, heated up, and typically vaporized in the HRHX, expanded in an expander (EXP) connected to a generator, and condensed in the condenser (CND).

![Figure 1: Rankine cycle](image-url)
The disadvantage of a conventional Rankine cycle is its relatively low efficiency due to large temperature differences between the hot and cold streams in the HRHX. The colder the heat source, the lower the efficiency.

U.S. Patent 7,278,264 describes a new cycle, a variation of the Rankine cycle that uses liquid or dense supercritical fluid (below its critical temperature, but above its critical pressure) instead of vapor in the expansion step.

Figure 2 (Figure 3 in the patent) shows one implementation of the cycle. Stream 110 is compressed in compressor 112. The resulting hot stream 114 is cooled in the heat-recovery exchanger 116, and exits the exchanger as stream 118. Stream 114 is the source of low grade heat.

Liquid working fluid in stream 120 is heated in heat-recovery exchanger 116 by indirect heat exchange with stream 114. The resulting stream 122, which is substantially liquid, is expanded in a two-phase dense-fluid expander, 124, to produce stream 126 containing mostly liquid with some vapor. Power generated by 124 can be used in the cycle or exported to the grid.

Stream, 126, at an intermediate pressure, is sent to phase separator 326, which produces vapor stream 327 and liquid stream 324. Vapor stream 327 is reheated in exchanger 116 and expanded in conventional vapor expander 330 to generate additional power yielding stream 332. Liquid stream 334 is expanded in dense-fluid expander 336 to generate more power yielding two-phase stream 338. Streams 332 and 338 are combined, giving stream 340, which is completely condensed in condenser 130.

Other configurations are described in a patent.

Figure 3 shows an Organic Rankine Cycle with Economizer/Regenerator (ECON) heat exchanger. Working fluid is fully vaporized in HRHX, expanded in EXP, and desuperheated in the ECON heat exchanger prior to condensation in CND and pumping.
Such a cycle is commonly used in low-grade heat recovery. An example is described in U.S. Patent 7,100,380.

![Figure 3. Organic Rankine Cycle](image)


**Problem Statement**

Air from a hot compressor is discharged at 65,000 lbmol/hr, 120 psia, and 230°F. Typically, it is cooled to 70°F in a shell-and-tube aftercooler. The heat is rejected to cooling water and, therefore, wasted. The aftercooler pressure drop does not exceed 5 psi. No high-grade heat source is available. This design project begins with an estimate of the thermodynamic availability of the hot stream; that is, the maximum work extracted when the stream is moved to its environmental state (77°F and 1 atm).

Then, the design team will consider the alternative cycle described in U.S. Patent 7,278,264 using ammonia as the working fluid and allowing up to 30 mol% vapor from the DFE discharge and an adiabatic efficiency of 75%. Cooling water will be at 65°F and the minimum temperature approach for the shell-and-tube condenser will be 5°F. The heat recovery heat exchanger is plate-and-fin with a minimum approach temperature difference, $\Delta T$, of 2°F and 20 NTUs, where $\text{NTU} = \Delta T_w / \text{LMTD}$, and $\Delta T_w$ is the cooling temperature change of the warm (air) stream. For the most promising design, the design team will determine the power generated and the capital investment required. Assuming a power cost of $2,000/KW, the competitiveness of this design will be considered. Note that ASPEN PLUS can be used for simulations of the designs.
The design team will begin with the configuration in Figure 1 and, depending on progress and perceived benefit, consider other configurations such as the one shown in Figure 2 (Figure 3 of the patent). Also, the design team will consider another way of recovering low-grade heat with the same heat source specifications as above. The team will select the cycle/method.

A possible candidate is a conventional organic Rankine cycle using pure working fluid such as propane or a mixture of components, such as hydrocarbons. Propane or another fluid will be completely vaporized in the HRHX. The amount of liquid at the expander’s discharge is not to exceed 15 mole%. The expander’s isentropic efficiency is 86%. Again, the power generated will be estimated – and the economics will be compared with those of the ammonia cycle. The design team is encouraged to search the literature and consider other low-grade heat-recovery methods, as well as other working fluids. The team should begin with a simple flowsheet and, if time permits, refine it to include additional features such as the economizer, etc.

Finally, if time permits, hot air at 350ºF will be considered. The design team will determine whether a break-even temperature exists – at which both cycles break even based on combined capital cost and power revenue.

In summary, the key elements of the project are to: a) determine the theoretical power limits, and b) compare novel technologies with current practice.

References

Patent searches can be performed using http://patft.uspto.gov/netahtml/PTO/searchadv.htm
Patents can be viewed in http://www.pate
General description of the Organic Rankine Cycle:

Organic Rankine Cycle used by WOW Energies is described in:

Appendix II: Patent

United States Patent

Brostow

PROCESS TO CONVERT LOW GRADE HEAT SOURCE INTO POWER USING DENSE FLUID EXPANDER

Inventor: Adam Adrian Brostow, Emmaus, PA (US)

Assignee: Air Products and Chemicals, Inc., Allentown, PA (US)

Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 365 days.

Appl. No.: 11/095,281

Filed: Mar. 31, 2005

Prior Publication Data


Int. Cl.

F01K 25/08 (2006.01)

U.S. Cl. .................................. 60/651; 60/671

Field of Classification Search ................................ 60/640; 60/651, 671

See application file for complete search history.

References Cited

U.S. PATENT DOCUMENTS


FOREIGN PATENT DOCUMENTS

* cited by examiner

Primary Examiner—Hoang Nguyen

[Signature]

ABSTRACT

A process to convert heat into power is set forth wherein, to make the cycle more suitable to low grade heat, the working fluid remains substantially in the liquid state after being heat exchanged against the heat source and a dense fluid expander is used in place of a conventional vapor expander to subsequently work expand the liquid working fluid.

10 Claims, 2 Drawing Sheets
A process to convert heat into power is set forth wherein to make the cycle more suitable to low grade heat, the working fluid remains substantially in the liquid state after being heat exchanged against the heat source and a dense fluid expander is used in place of a conventional vapor expander to subsequently work expand the liquid working fluid.
Figure 1

Figure 2
Figure 3

Figure 4
1
PROCESS TO CONVERT LOW GRADE HEAT SOURCE INTO POWER USING DENSE FLUID EXPANDER

BACKGROUND OF THE INVENTION

Heat can be converted into power by the well known Rankine cycle as follows:
Step 1: pumping a liquid working fluid to an elevated pressure;
Step 2: heating the resulting elevated pressure liquid working fluid by indirect heat exchange against the heat source where said heating results in:
(a) boiling the working fluid; and
(b) preferably superheating the boil-off to a sufficient degree to ensure the working fluid remains substantially in the vapor state throughout step 3's work expansion step;
Step 3: work expanding (defined herein as expanding at substantially constant entropy) the resulting heated working fluid in a turbine expander;
Step 4: condensing the work expanded working fluid by heat exchanging against cooling water to prepare the working fluid for a new cycle of steps 1 through 3.

In one variation (herein, the supercritical variation such as supercritical steam cycles), the liquid working fluid is pumped to a supercritical pressure (i.e., a pressure above the liquid's critical pressure) in step 1 and heated to a supercritical temperature (i.e., a temperature above the liquid's critical temperature) in step 2.

In another variation, the thermodynamic efficiency of step 3's work expansion step is increased by using a multi-stage expander wherein the working fluid is re-heated against the heat source between stages.

In another variation, the working fluid is preheated against a low grade heat source prior to boiling the working fluid against a higher grade heat source (See for example U.S. Pat. No. 3,875,069 and U.S. Pat. No. 4,182,127).

The present invention differs from the conventional application of the Rankine cycle in a significant way. In particular, instead of requiring the heat source to be of sufficiently high temperature or "high grade" to boil or superheat the working fluid in step 2 (or heat working fluid to supercritical temperature in case of supercritical cycle), a dense fluid expander is utilized in step 3.

In this fashion, the working fluid is allowed to be a liquid at the end of step 2 (or at least mostly a liquid as there are dense fluid expanders that can tolerate some vapor at the inlet) resulting in an expander discharge at the end of step 3 containing a vapor portion and a (typically heavier) liquid portion. Accordingly, the present invention is suitable for relatively low temperature (typically 100°F or less) or "low grade" heat sources (often referred to as "waste heat") that are incapable of boiling/superheating the working fluid in step 2 (or heat heating working fluid to supercritical temperature in case of supercritical cycle). On at least incepl of providing such an amount of heat while still allowing, as required in step 4, the expanded working fluid to be condensed without any refrigeration beyond ordinary cooling water.

In addition to its applicability to low grade heat, the present invention also avoids the thermodynamic penalty associated with employing a boiling liquid to recover heat. (See for example U.S. Patent No. 1300677 which utilizes boiling fluid to recover high grade heat of compression.) In particular, since a liquid (or at least a single component liquid) boils at a constant temperature, the associated heat exchanger has large temperature differences between the hot and cold streams (i.e., very non-"tight" cooling curves) which the present invention avoids. (Although the supercritical variations of the Rankine cycle also avoids this thermodynamic penalty associated with employing a boiling liquid to recover heat, if the fluid's critical temperature is below the temperature of the low grade heat source, the liquid condensed at the cooling water temperature is relatively close to the fluid's critical temperature and consequently the pump work will be too high relative to the expander work for the cycle to be efficient.)

Of course, as the skilled practitioner can readily appreciate, there is a thermodynamic (and mechanical complexity) penalty associated with the present invention's work expansion of a gas vis-a-vis the conventional work expansion of a vapor. However, recent advances in dense fluid expanders, coupled with the ever increasing energy costs, are working to justify the present invention's use a dense fluid expander to convert low grade heat sources into power. Examples of such low grade heat include compressor discharge, geothermal sources (such as hot spring) and the heat from solar collectors.

Henceforth, the application of two-phase dense fluid expanders has been limited to refrigeration cycles where, prior to working expanding the working fluid, the working fluid is circulated (e.g., to take advantage of refrigeration producing effect when a fluid is work expanded) instead of heated as in present cycle (e.g., to take advantage of work producing effect when a fluid is work expanded). For example, U.S. Pat. No. 5,264,201 teaches use of a two-phase dense fluid expander in an air separation plant. U.S. Pat. No. 5,763,081 teaches expanding liquid natural gas in a two-phase dense fluid expander. Two-phase dense fluid expanders have also been proposed in a standard vapor compression refrigeration cycle as a replacement for a theoretical (Borg-Thompson) valve.

BRIEF SUMMARY OF THE INVENTION

The present invention is a process to convert heat into power wherein, to make the process more suitable to low grade heat, the working fluid remains substantially in the liquid state after being heat exchanged against the heat source and a dense fluid expander is used in place of a conventional vapor expander to subsequently work expand the liquid working fluid.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic drawing of one embodiment of the present invention.
FIG. 2 is a schematic drawing of another embodiment of the present invention.
FIG. 3 is a schematic drawing of another embodiment of the present invention.
FIG. 4 is a schematic drawing of another embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention is a process to convert a heat source into power comprising:
Step 1: pumping a liquid working fluid to an elevated pressure;
Step 2: heating the resulting elevated pressure liquid working fluid by indirect heat exchange against the heat source wherein, at the end of this step 2, the working fluid remains substantially in the liquid state.

Step 3: working the resulting heated working fluid in a dense fluid expander to generate a low pressure liquid, a low pressure gas, and solid power, and

Step 4: condensing the low pressure gas from step 3 by indirect heat exchange against a cooling fluid and re-combining the resultant condensed low pressure gas with the low pressure liquid from step 3 to prepare the working fluid for a new cycle of steps 1 through 4.

As used herein, the term liquid is primarily intended to refer to a subcritical fluid (i.e., a liquid below both its critical pressure and critical temperature). Accordingly, in one embodiment of the present invention, the liquid is a subcritical fluid throughout the entire cycle.

However, the use of a “supercritical liquid” (defined herein as the fluid at supercritical pressure but subcritical temperature) is also within the scope of the present invention. Accordingly, in another embodiment of the present invention (hereinafter, the partial supercritical embodiment), the liquid working fluid is pumped to a supercritical pressure in step 1 and heated to a temperature below its supercritical temperature in step 2. (Contrast this partial supercritical embodiment with supercritical variation of Rankine cycle discussed under Background section where the supercritical pressure working fluid from step 1 is heated to a temperature above its supercritical temperature in step 2.)

In another embodiment of the present invention, the heat source is at low temperature below 200°F.

In another embodiment of the present invention, the heat source is at low-grade heat source comprising the discharge from a Rankine cycle

In another embodiment of the present invention, the cooling fluid comprises at least two components mixed together.

Referring to the embodiment of the present invention depicted in FIG. 1, gas stream 110 is compressed in compressor 112, resulting hot stream 114 is cooled in the heat recovery exchanger 114, and exits the exchanger as stream 116. Liquid working fluid 120 is heated in 116 by indirect heat exchange against stream 116. The resulting subcritical liquid stream 122 is expanded in a two-stage dense fluid expander 124 to produce steam 126 consisting mostly liquid with some vapor. Steam 126 is then cooled and condensed in condenser 130. The resulting liquid stream 131 is pumped in pump 132 to produce steam 126. Compressor 112 can be single-stage or multiple stages with intercoolers or without intercoolers (adiabatic compression). The power recovery system can be present from the beginning or added at a retrofit.

FIG. 2 is similar to FIG. 1. Its embodiment (corresponding streams and equipment) are identified with same numbers except the heat is recovered from a multiple stage compressor. In particular, compressed, cooled gas stream 110 is now expanded in compressor 212. The resulting hot stream 214 is cooled in 216 and exits the exchanger as stream 218. Multiple heat exchangers can be used in place of a single exchanger 116 with working fluid distributed between the exchangers.

FIG. 3 is similar to FIG. 1. Its embodiment (corresponding streams and equipment) are identified with same numbers except a vapor portion of 126, now at an intermediate pressure, is separated in phase separator 326 to produce vapor stream 327 and liquid stream 324. Vapor stream 327 is re-heat in 116 and expanded in vapor expander 328 to generate additional pressure and produce steam 332. Liquid stream 334 is expanded in additional dense fluid expander 336 to generate more power to produce steam two-phase stream 338. Streams 332 and 334 are combined to produce steam 340 that is completely condensed in condenser 130.

FIG. 4 is similar to FIG. 1. Its embodiment (corresponding streams and equipment) are identified with same numbers except a vapor portion of stream 322, after being separated in phase separator 426, is expanded in vapor expander 430 to generate additional pressure and produce steam 432. The liquid portion 434 is expanded in dense fluid expander 436 to generate more power to produce steam two-phase stream 438. Streams 432 and 438 are combined to produce steam 440 that is completely condensed in condenser 130.

The configuration shown in FIG. 1 is offered to demonstrate the efficiency of the present invention. Drier air at rate of 100 lb mole/1 (28.96 lb/hr) is compressed in a single-stage compressor from 14.7 psia to 70°F to 26.46 psia to 70°F with 3.5°F (15.1°C). The compressor’s adiabatic efficiency is 85% while the brake horsepower is 311.7. The compressed air, now at 183.8°F, goes to a low recovery exchanger where it is cooled down to 78.6°F against liquid ammonia. Liquid ammonia enters the heat recovery exchanger at the rate of 390.8 lb mole/1 (5550.0 lb/hr), 268.6 psia, and 72.1°F and is heated to 179.7°F by indirect heat exchange with above-mentioned air stream. The cooling tower in the heat exchanger is filled with the liquid ammonia mean temperature difference of 3.3°F.

Hot liquid ammonia is then expanded in a dense fluid expander down to 128.7 psia. It is now at 70°F and contains 25.3% vapor on molal basis. The expander adiabatic efficiency is 75%; brake horsepower is 24.0. The partially flashed low pressure ammonia is completely condensed in a condenser against cooling water (cooling water or other coolant’s temperature determines expander’s outlet pressure), pumped to 268.6 psia, and introduced to the heat recovery exchanger to closer the cycle. The pump’s adiabatic efficiency is 85%; brake horsepower is 5.5.

The net power recovered is equal to the power generated by the expander minus the power consumed by the pump. It is 18.5 HP or 5.9% of the original power of compression. The impact of equipment pressure drops (neglected in this example) is not expected to significantly change this number.

In particular, the invention claimed is:

1. A process to convert a heat source into power comprising:
   Step 1: pumping a liquid working fluid to an elevated pressure;
   Step 2: heating the resulting elevated pressure liquid working fluid by indirect heat exchange against the heat source wherein, at the end of this step 2, the working fluid remains substantially in the liquid state;
   Step 3: working the resulting heated working fluid in a dense fluid expander to generate a low pressure liquid, a low pressure gas and solid power;
Step 4: condensing the low pressure gas from step 3 by indirect heat exchange against a cooling fluid and re-combining the resultant condensed low pressure gas with the low pressure liquid from step 3 to prepare the working fluid for a new cycle of steps 1 through 3.

2. The process of claim 1 wherein the liquid is a subcritical liquid throughout the entire cycle.

3. The process of claim 1 wherein the liquid working fluid is plumbed to a supercritical pressure in step 1 and heated to a temperature below its supercritical temperature in step 2.

4. The process of claim 1 wherein the heat source is at temperature below 200 F.

5. The process of claim 1 wherein the heat source is a low grade heat source comprising the discharge from a compressor.

6. The process of claim 1 wherein the cooling fluid used in step 4 comprises cooling water.

7. The process of claim 1 wherein the working fluid comprises ammonia.

8. The process of claim 1 wherein the working fluid comprises at least two components mixed together.

9. The process of claim 1 wherein step 3 comprises:
   a) work expanding the heated working fluid from step 2 to an intermediate pressure in a first dense fluid expander to generate an intermediate low pressure liquid, an intermediate low pressure gas and a portion of said power;
   b) separating the intermediate low pressure liquid from the intermediate low pressure liquid;
   c) heating the intermediate low pressure vapor by indirect heat exchange against the heat source; and
   d) further work expanding the intermediate low pressure vapor in a vapor expander to generate a second portion of said power and the low pressure vapor that is condensed in step 4; and

10. The process of claim 1 wherein a portion of the working fluid is vaporized in step 2 and separated work expanded in a vapor expander to generate a portion of said power.

* * * * *
### Appendix III: ASPEN Input, Unit and Stream Results

<table>
<thead>
<tr>
<th>STREAM ID</th>
<th>114</th>
</tr>
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<tbody>
<tr>
<td>FROM</td>
<td>----</td>
</tr>
<tr>
<td>TO</td>
<td>116</td>
</tr>
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</table>

**SUBSTREAM:** MIXED

**PHASE:** VAPOR

**COMPONENTS:** LBMOL/HR

<table>
<thead>
<tr>
<th>Component</th>
<th>LBMOL/HR</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR</td>
<td>6.5000E+04</td>
</tr>
<tr>
<td>AMMONIA</td>
<td>0.0</td>
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**TOTAL FLOW:**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>LBMOL/HR</td>
<td>6.5000E+04</td>
</tr>
<tr>
<td>LB/HR</td>
<td>1.8818E+06</td>
</tr>
<tr>
<td>CUFT/HR</td>
<td>4.0160E+06</td>
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**STATE VARIABLES:**

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<td>PRES</td>
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<td>LFRAC</td>
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**ENTHALPY:**

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<tr>
<td>BTU/LB</td>
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<td>BTU/HR</td>
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**ENTROPY:**

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<tr>
<td>BTU/LB-R</td>
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**DENSITY:**

<table>
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<td>LB/CUFT</td>
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<td>AVG MW</td>
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<table>
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<td>TO</td>
<td>----</td>
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**SUBSTREAM:** MIXED

**PHASE:** VAPOR

**COMPONENTS:** LBMOL/HR

<table>
<thead>
<tr>
<th>Component</th>
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</tr>
</thead>
<tbody>
<tr>
<td>AIR</td>
<td>6.5000E+04</td>
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<tr>
<td>AMMONIA</td>
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</table>

**TOTAL FLOW:**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>LBMOL/HR</td>
<td>6.5000E+04</td>
</tr>
<tr>
<td>LB/HR</td>
<td>1.8818E+06</td>
</tr>
<tr>
<td>CUFT/HR</td>
<td>3.3039E+06</td>
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**STATE VARIABLES:**

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<tbody>
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PRES PSIA 115.0000
VFRAC 1.0000
LFRAC 0.0
SFRAC 0.0
ENTHALPY:
  BTU/LBMOL 39.2354
  BTU/LB 1.3552
  BTU/HR 2.5503+06
ENTROPY:
  BTU/LBMOL-R -4.0095
  BTU/LB-R -0.1385
DENSITY:
  LBMOL/CUFT 1.9673-02
  LB/CUFT 0.5696
AVG MW 28.9509

120
---

STREAM ID 120
FROM : 132
TO : 116

SUBSTREAM: MIXED
PHASE: LIQUID
COMPONENTS: LBMOL/HR
  AIR 0.0
  AMMONIA 1.7500+04
TOTAL FLOW:
  LBMOL/HR 1.7500+04
  LB/HR 2.9803+05
  CUFT/HR 7890.1871
STATE VARIABLES:
  TEMP F 72.9464
  PRES PSIA 900.0000
  VFRAC 0.0
  LFRAC 1.0000
  SFRAC 0.0
ENTHALPY:
  BTU/LBMOL -2.9003+04
  BTU/LB -1702.9694
  BTU/HR -5.0754+08
ENTROPY:
  BTU/LBMOL-R -45.4427
  BTU/LB-R -2.6683
DENSITY:
  LBMOL/CUFT 2.2179
  LB/CUFT 37.7728
AVG MW 17.0306

122
---

STREAM ID 122
FROM : 116
TO : 124
SUBSTREAM: MIXED  
PHASE: LIQUID  
COMPONENTS: LBMOL/HR  
   AIR          0.0  
   AMMONIA     1.7500+04  
TOTAL FLOW:  
   LBMOL/HR    1.7500+04  
   LB/HR       2.9803+05  
   CUFT/HR     1.0397+04  
STATE VARIABLES:  
   TEMP   F  209.8574  
   PRES   PSIA  895.0000  
   VFRAC  0.0  
   LFRAC  1.0000  
   SFRAC  0.0  
ENTHALPY:  
   BTU/LBMOL -2.5549+04  
   BTU/LB -1500.1703  
   BTU/HR -4.4710+08  
ENTROPY:  
   BTU/LBMOL-R -39.7257  
   BTU/LB-R -2.3326  
DENSITY:  
   LBMOL/CUFT  1.6832  
   LB/CUFT  28.6650  
AVG MW  17.0306  

---

STREAM ID  126  
FROM :  124  
TO :  326  

SUBSTREAM: MIXED  
PHASE: MIXED  
COMPONENTS: LBMOL/HR  
   AIR          0.0  
   AMMONIA     1.7500+04  
TOTAL FLOW:  
   LBMOL/HR    1.7500+04  
   LB/HR       2.9803+05  
   CUFT/HR     1.1830+05  
STATE VARIABLES:  
   TEMP   F  109.0104  
   PRES   PSIA  244.6396  
   VFRAC  0.2940  
   LFRAC  0.7060  
   SFRAC  0.0  
ENTHALPY:  
   BTU/LBMOL -2.5773+04  
   BTU/LB -1513.3208  
   BTU/HR -4.5102+08  
ENTROPY:  
   BTU/LBMOL-R -39.5898
BTU/LB-R
DENSITY:
LBMOL/CUFT 0.1479
LB/CUFT 2.5193
AVG MW 17.0306

---

STREAM ID 131
FROM : B3
TO : ----

SUBSTREAM: MIXED
PHASE: LIQUID
COMPONENTS: LBMOL/HR
AIR 0.0
AMMONIA 1.7500+04
TOTAL FLOW:
LBMOL/HR 1.7500+04
LB/HR 2.9803+05
CUFT/HR 7855.8150
STATE VARIABLES:
TEMP F 69.7952
PRES PSIA 128.0000
VFRAC 0.0
LFRAC 1.0000
SFRAC 0.0
ENTHALPY:
BTU/LBMOL -2.9087+04
BTU/LB -1707.9324
BTU/HR -5.0902+08
ENTROPY:
BTU/LBMOL-R -45.4487
BTU/LB-R -2.6687
DENSITY:
LBMOL/CUFT 2.2276
LB/CUFT 37.9381
AVG MW 17.0306

---

STREAM ID 327
FROM : 326
TO : 116

MAX CONV. ERROR: 2.6569-10
SUBSTREAM: MIXED
PHASE: VAPOR
COMPONENTS: LBMOL/HR
AIR 0.0
AMMONIA 5154.2573
TOTAL FLOW:
LBMOL/HR 5154.2573
LB/HR  8.7780+04
CUFT/HR  1.1309+05
STATE VARIABLES:
  TEMP   F  108.7423
  PRES   PSIA  243.6396
  VFRAC   1.0000
  LFRAC   0.0
  SFRAC   0.0
ENTHALPY:
  BTU/LBMOL -1.9877+04
  BTU/LB -1167.1400
  BTU/HR -1.0245+08
ENTROPY:
  BTU/LBMOL-R -29.2154
  BTU/LB-R -1.7155
DENSITY:
  LBMOL/CUFT  4.5578-02
  LB/CUFT  0.7762
AVG MW  17.0306

---

STREAM ID  328
FROM :  116
TO :  330
SUBSTREAM: MIXED
PHASE:  VAPOR
COMPONENTS: LBMOL/HR
  AIR   0.0
  AMMONIA  5154.2573
TOTAL FLOW:
  LBMOL/HR  5154.2573
  LB/HR  8.7780+04
  CUFT/HR  1.4442+05
STATE VARIABLES:
  TEMP   F  209.8574
  PRES   PSIA  238.6396
  VFRAC   1.0000
  LFRAC   0.0
  SFRAC   0.0
ENTHALPY:
  BTU/LBMOL -1.8865+04
  BTU/LB -1107.7002
  BTU/HR -9.7234+07
ENTROPY:
  BTU/LBMOL-R -27.5385
  BTU/LB-R -1.6170
DENSITY:
  LBMOL/CUFT  3.5689-02
  LB/CUFT  0.6078
AVG MW  17.0306

---
STREAM ID 332
FROM : 330
TO : B4

SUBSTREAM: MIXED
PHASE: VAPOR
COMPONENTS: LBMOL/HR
   AIR  0.0
   AMMONIA  5154.2573

TOTAL FLOW:
   LBMOL/HR  5154.2573
   LB/HR  8.7780+04
   CUFT/HR  2.4049+05

STATE VARIABLES:
   TEMP   F  129.1919
   PRES   PSIA  128.0000
   VFRAC  1.0000
   LFRAC  0.0
   SFRAC  0.0

ENTHALPY:
   BTU/LBMOL  -1.9477+04
   BTU/LB  -1143.6685
   BTU/HR  -1.0039+08

ENTROPY:
   BTU/LBMOL-R  -27.3531
   BTU/LB-R  -1.6061

DENSITY:
   LBMOL/CUFT  2.1433-02
   LB/CUFT  0.3650
   AVG MW  17.0306

334
---

STREAM ID 334
FROM : 326
TO : 336

SUBSTREAM: MIXED
PHASE: LIQUID
COMPONENTS: LBMOL/HR
   AIR  0.0
   AMMONIA  1.2346+04

TOTAL FLOW:
   LBMOL/HR  1.2346+04
   LB/HR  2.1025+05
   CUFT/HR  5872.1113

STATE VARIABLES:
   TEMP   F  108.7423
   PRES   PSIA  243.6396
   VFRAC  0.0
   LFRAC  1.0000
   SFRAC  0.0

ENTHALPY:
   BTU/LBMOL  -2.8234+04
Low-Grade Heat Recovery

BTU/LB  -1657.8487
BTU/HR  -3.4857E+08

ENTROPY:
  BTU/LBMOL-R  -43.9179
  BTU/LB-R     -2.5788

DENSITY:
  LBMOL/CUFT  2.1024
  LB/CUFT     35.8057
AVG MW    17.0306

---

STREAM ID    338
FROM:        336
TO:          339

SUBSTREAM: MIXED
PHASE:       MIXED
COMPONENTS: LBMOL/HR
  AIR          0.0
  AMMONIA     1.2346E+04

TOTAL FLOW:
  LBMOL/HR  1.2346E+04
  LB/HR     2.1025E+05
  CUFT/HR   4.9891E+04

STATE VARIABLES:
  TEMP       F  70.2309
  PRES       PSIA 129.0000
  VFRAC      8.9281
  LFRAC      0.9107
  SFRAC      0.0

ENTHALPY:
  BTU/LBMOL  -2.8269E+04
  BTU/LB     -1659.9264
  BTU/HR     -3.4901E+08

ENTROPY:
  BTU/LBMOL-R -43.9061
  BTU/LB-R    -2.5781

DENSITY:
  LBMOL/CUFT  0.2475
  LB/CUFT     4.2143
AVG MW    17.0306

---

STREAM ID    340
FROM:        B4
TO:          130

SUBSTREAM: MIXED
PHASE:       VAPOR
COMPONENTS: LBMOL/HR
  AIR          0.0
  AMMONIA     6268.2056

TOTAL FLOW:
  LBMOL/HR  6268.2056
  LB/HR    1.0675+05
  CUFT/HR  2.8625+05
STATE VARIABLES:
  TEMP    F  118.6564
  PRES    PSIA  128.0000
  VFRAC   1.0000
  LFRAC   0.0
  SFRAC   0.0
ENTHALPY:
  BTU/LBMOL  -1.9575+04
  BTU/LB     -1149.3995
  BTU/HR     -1.2270+08
ENTROPY:
  BTU/LBMOL-R -27.5203
  BTU/LB-R    -1.6159
DENSITY:
  LBMOL/CUFT  2.1898-02
  LB/CUFT     0.3729
AVG MW      17.0306

---

STREAM ID    341
FROM :       339
TO :         B3

PHASE:       LIQUID
COMPONENTS: LBMOL/HR
  AIR          0.0
  AMMONIA      1.1232+04
TOTAL FLOW:
  LBMOL/HR    1.1232+04
  LB/HR       1.9128+05
  CUFT/HR     5041.9942
STATE VARIABLES:
  TEMP    F  69.7952
  PRES    PSIA  128.0000
  VFRAC   0.0
  LFRAC   1.0000
  SFRAC   0.0
ENTHALPY:
  BTU/LBMOL  -2.9087+04
  BTU/LB      -1707.9295
  BTU/HR      -3.2670+08
ENTROPY:
  BTU/LBMOL-R -45.4487
  BTU/LB-R     -2.6687
DENSITY:
  LBMOL/CUFT  2.2276
  LB/CUFT     37.9381
AVG MW      17.0306
342
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<tr>
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**SUBSTREAM:** MIXED  
**PHASE:** VAPOR  
**COMPONENTS:** LBMOL/HR  
- AIR: 0.0  
- AMMONIA: 1113.9484

**TOTAL FLOW:**  
- LBMOL/HR: 1113.9484  
- LB/HR: 1.8971+04  
- CUFT/HR: 4.5655+04

**STATE VARIABLES:**  
- TEMP: 69.7952 (F)  
- PRES: 128.0000 (PSIA)  
- VFRAC: 1.0000  
- LFRAC: 0.0  
- SFRAC: 0.0

**ENTHALPY:**  
- BTU/LBMOL: -2.0027+04  
- BTU/LB: -1175.9171  
- BTU/HR: -2.2309+07

**ENTROPY:**  
- BTU/LBMOL-R: -28.3362  
- BTU/LB-R: -1.6638

**DENSITY:**  
- LBMOL/CUFT: 2.4399-02  
- LB/CUFT: 0.4155  
- AVG MW: 17.0306

343
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</table>

**SUBSTREAM:** MIXED  
**PHASE:** LIQUID  
**COMPONENTS:** LBMOL/HR  
- AIR: 0.0  
- AMMONIA: 6268.2056

**TOTAL FLOW:**  
- LBMOL/HR: 6268.2056  
- LB/HR: 1.0675+05  
- CUFT/HR: 2813.7959

**STATE VARIABLES:**  
- TEMP: 69.7887 (F)  
- PRES: 128.0000 (PSIA)  
- VFRAC: 0.0  
- LFRAC: 1.0000  
- SFRAC: 0.0
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<tbody>
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<td>BTU/LBMOL</td>
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<td>AVG MW</td>
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</table>
### Low-Grade Heat Recovery

**BLOCK: 124 MODEL: COMPR**

| Property Option Set | RK-SOAVE STANDARD RK-EQUATION OF STATE |

**INLET STREAM:** 122  
**OUTLET STREAM:** 126

**FEED STREAM IS BELOW DEW POINT**

***** MASS AND ENERGY BALANCE *****

<table>
<thead>
<tr>
<th>DIFF.</th>
<th>TOTAL BALANCE</th>
<th>IN</th>
<th>OUT</th>
<th>RELATIVE</th>
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<td>17500.0</td>
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<tr>
<td>MASS (LB/HR)</td>
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<td>298035.</td>
<td>0.0000</td>
<td></td>
</tr>
<tr>
<td>ENTHALPY (BTU/HR)</td>
<td>-0.447103E+09</td>
<td>-0.451022E+09</td>
<td>0.868983E-02</td>
<td></td>
</tr>
</tbody>
</table>

***** INPUT DATA *****

**ISENTROPIC TURBINE**

**OUTLET PRESSURE PSIA** 244.640  
**ISENTRONIC EFFICIENCY** 0.75000  
**MECHANICAL EFFICIENCY** 1.00000

***** RESULTS *****

**INDICATED HORSEPOWER REQUIREMENT HP** -1,540.35
**BRAKE HORSEPOWER REQUIREMENT HP** -1,540.35
**NET WORK REQUIRED HP** -1,540.35
**POWER LOSSES HP** 0.0
**ISENTRONIC HORSEPOWER REQUIREMENT HP** -2,053.79
**CALCULATED OUTLET TEMP F** 109.010
**ISENTRONIC TEMPERATURE F** 109.010
**EFFICIENCY (POLYTR/ISENTR) USED** 0.75000
**OUTLET VAPOR FRACTION** 0.29399
**HEAD DEVELOPED, FT-LBF/LB** -13,644.4
**MECHANICAL EFFICIENCY USED** 1.00000
**INLET HEAT CAPACITY RATIO** 1.00000
**INLET VOLUMETRIC FLOW RATE, CUFT/HR** 10,400.0
**OUTLET VOLUMETRIC FLOW RATE, CUFT/HR** 118,302.
**AV. ISENT. VOL. EXPONENT** 0.53345
**AV. ISENT. TEMP EXPONENT** 1.14412

**BLOCK: 132 MODEL: PUMP**

| Property Option Set | RK-SOAVE STANDARD RK-EQUATION OF STATE |

**INLET STREAM:** 131-A  
**OUTLET STREAM:** 120
PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

DIFF.
TOTAL BALANCE
MOLE(LBMOL/HR)  17500.0     17500.0     0.00000
MASS(LB/HR )   298035.      298035.     0.00000
ENTHALPY(BTU/HR ) -0.508947E+09 -0.507544E+09 -0.275549E-02

*** INPUT DATA ***

OUTLET PRESSURE  PSIA                               900.000
PUMP EFFICIENCY                                         0.80000
DRIVER EFFICIENCY                                       1.00000

FLASH SPECIFICATIONS:
LIQUID PHASE CALCULATION
NO FLASH PERFORMED
MAXIMUM NUMBER OF ITERATIONS                            30
TOLERANCE                                                0.000100000

*** RESULTS ***

VOLUMETRIC FLOW RATE  CUFT/HR                        7,858.03
PRESSURE CHANGE PSI                                771.539
NPSH AVAILABLE  FT-LBF/LB                           0.0
FLUID POWER HP                                      440.930
BRAKE POWER HP                                      551.162
ELECTRICITY KW                                      411.001
PUMP EFFICIENCY USED                                0.80000
NET WORK REQUIRED  HP                               551.162
HEAD DEVELOPED FT-LBF/LB                            2,929.32

BLOCK:  130  MODEL: HEATER

--------------------------
INLET STREAM:          340
OUTLET STREAM:         343
PROPERTY OPTION SET:   RK-SOAVE STANDARD RKS EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

DIFF.
TOTAL BALANCE
MOLE(LBMOL/HR)  6268.21     6268.21     0.00000
MASS(LB/HR )   106751.      106751.     0.00000
ENTHALPY(BTU/HR ) -0.122700E+09 -0.182324E+09 0.327025

*** INPUT DATA ***

TWO PHASE PV FLASH
PRESSURE DROP PSI                                  0.0
VAPOR FRACTION                                     0.0
MAXIMUM NO. ITERATIONS                             30
CONVERGENCE TOLERANCE                              0.000100000
*** RESULTS ***

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outlet Temperature F</td>
<td>69.789</td>
</tr>
<tr>
<td>Outlet Pressure PSIA</td>
<td>128.00</td>
</tr>
<tr>
<td>Heat Duty BTU/HR</td>
<td>-0.59625E+08</td>
</tr>
<tr>
<td>Outlet Vapor Fraction</td>
<td>0.0000</td>
</tr>
<tr>
<td>Pressure-Drop Correlation Parameter</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

V-L Phase Equilibrium:

<table>
<thead>
<tr>
<th>Component</th>
<th>F(I)</th>
<th>X(I)</th>
<th>Y(I)</th>
<th>K(I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td>0.99990</td>
</tr>
</tbody>
</table>

Block: 326  Model: FLASH2

Inlet Stream: 126
Outlet Vapor Stream: 327
Outlet Liquid Stream: 334
Property Option Set: RK-SOAVE  Standard RKS Equation of State

*** Mass and Energy Balance ***

---

*** Input Data ***

- Two Phase PQ Flash
- Pressure Drop PSI: 1.0000
- Specified Heat Duty BTU/HR: 0.0
- Maximum No. Iterations: 30
- Convergence Tolerance: 0.000100000

*** RESULTS ***

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outlet Temperature F</td>
<td>108.74</td>
</tr>
<tr>
<td>Outlet Pressure PSIA</td>
<td>243.64</td>
</tr>
<tr>
<td>Vapor Fraction</td>
<td>0.29453</td>
</tr>
</tbody>
</table>

V-L Phase Equilibrium:

<table>
<thead>
<tr>
<th>Component</th>
<th>F(I)</th>
<th>X(I)</th>
<th>Y(I)</th>
<th>K(I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

Block: 330  Model: COMPR

Inlet Stream: 328
Outlet Stream: 332
Property Option Set: RK-SOAVE  Standard RKS Equation of State

*** Mass and Energy Balance ***
**Low-Grade Heat Recovery**

<table>
<thead>
<tr>
<th>DIFF.</th>
<th>IN</th>
<th>OUT</th>
<th>RELATIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TOTAL BALANCE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOLE (LB/HR)</td>
<td>5154.26</td>
<td>5154.26</td>
<td>0.00000</td>
</tr>
<tr>
<td>MASS (LB/HR)</td>
<td>87779.9</td>
<td>87779.9</td>
<td>0.00000</td>
</tr>
<tr>
<td>ENTHALPY (BTU/HR)</td>
<td>-0.972338E+08</td>
<td>-0.100391E+09</td>
<td>0.314500E-01</td>
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</tbody>
</table>

*** INPUT DATA ***

**ISENTROPIC TURBINE**

<table>
<thead>
<tr>
<th>OUTLET PRESSURE (PSIA)</th>
<th>128.000</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISENTROPIC EFFICIENCY</td>
<td>0.85000</td>
</tr>
<tr>
<td>MECHANICAL EFFICIENCY</td>
<td>1.00000</td>
</tr>
</tbody>
</table>

*** RESULTS ***

| INDICATED HORSEPOWER REQUIREMENT (HP) | -1,240.87 |
| BRAKE HORSEPOWER REQUIREMENT (HP)    | -1,240.87 |
| NET WORK REQUIRED (HP)               | -1,240.87 |
| POWER LOSSES (HP)                    | 0.0       |
| ISENTROPIC HORSEPOWER REQUIREMENT (HP)| -1,459.84 |
| CALCULATED OUTLET TEMPERATURE (F)    | 129.192   |
| ISENTROPIC TEMPERATURE (F)           | 117.522   |
| EFFICIENCY (POLYTR/ISENTR) USED      | 0.85000   |
| OUTLET VAPOR FRACTION                | 1.00000   |
| HEAD DEVELOPED, FT-LBF/LB            | -32,928.8 |
| MECHANICAL EFFICIENCY USED           | 1.00000   |
| INLET VOLUME RATIO                   | 1.37628   |
| INLET VOLUME FLOW RATE, CUFT/HR      | 144,420.  |
| OUTLET VOLUME FLOW RATE, CUFT/HR     | 240,486.  |
| INLET COMPRESSIBILITY FACTOR        | 0.93063   |
| OUTLET COMPRESSIBILITY FACTOR       | 0.94507   |
| AV. ISENT. VOL. EXPONENT             | 1.28144   |
| AV. ISENT. TEMP EXPONENT             | 1.31272   |
| AV. ACTUAL VOL. EXPONENT             | 1.22158   |
| AV. ACTUAL TEMP EXPONENT             | 1.25959   |

BLOCK: 336  MODEL: COMPR

-----------------------------

INLET STREAM: 334
OUTLET STREAM: 338
PROPERTY OPTION SET: RK-SOAVE STANDARD RKS EQUATION OF STATE

**********************************************************************
*                                                                     *
*     FEED STREAM IS BELOW DEW POINT                                 *
*                                                                     *
**********************************************************************

*** MASS AND ENERGY BALANCE ***

<table>
<thead>
<tr>
<th>DIFF.</th>
<th>IN</th>
<th>OUT</th>
<th>RELATIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TOTAL BALANCE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOLE (LB/HR)</td>
<td>12345.7</td>
<td>12345.7</td>
<td>0.00000</td>
</tr>
</tbody>
</table>
Low-Grade Heat Recovery

MASS (LB/HR) 210255. 210255. 0.00000
ENTHALPY (BTU/HR) -0.348571E+09 -0.349008E+09 0.125166E-02

*** INPUT DATA ***

ISENTERIC TURBINE
OUTLET PRESSURE PSIA 129.000
ISENTERIC EFFICIENCY 0.85000
MECHANICAL EFFICIENCY 1.00000

*** RESULTS ***

INDICATED HORSEPOWER REQUIREMENT HP -171.684
BRAKE HORSEPOWER REQUIREMENT HP -171.684
NET WORK REQUIRED HP -171.684
POWER LOSSES HP 0.0
ISENTERIC HORSEPOWER REQUIREMENT HP -201.982
CALCULATED OUTLET TEMP F 70.2309
ISENTERIC TEMPERATURE F 70.2333
EFFICIENCY (POLYTR/ISENTR) USED 0.85000
OUTLET VAPOR FRACTION 0.089281
HEAD DEVELOPED, FT-LBF/LB -1,902.09
MECHANICAL EFFICIENCY USED 1.00000
INLET HEAT CAPACITY RATIO 1.00000
INLET VOLUMETRIC FLOW RATE, CUFT/HR 5,872.11
OUTLET VOLUMETRIC FLOW RATE, CUFT/HR 49,890.5
INLET COMPRESSIBILITY FACTOR 0.018998
OUTLET COMPRESSIBILITY FACTOR 0.091673
AV. ISENT. VOL. EXPONENT 0.29816
AV. ISENT. TEMP EXPONENT 1.12400
AV. ACTUAL VOL. EXPONENT 0.29719
AV. ACTUAL TEMP EXPONENT 1.12401

BLOCK: 339 MODEL: FLASH2

---------------------------
INLET STREAM: 338
OUTLET VAPOR STREAM: 342
OUTLET LIQUID STREAM: 341
PROPERTY OPTION SET: RK-SOAVE STANDARD RK'S EQUATION OF STATE

*** MASS AND ENERGY BALANCE ***

IN OUT RELATIVE
TOTAL BALANCE
MOLE (LBMOH/HR) 12345.7 12345.7 0.00000
MASS (LB/HR) 210255. 210255. 0.00000
ENTHALPY (BTU/HR) -0.349008E+09 -0.349008E+09 0.120541E-07

*** INPUT DATA ***

TWO PHASE PQ FLASH
PRESSURE DROP PSI 1.00000
SPECIFIED HEAT DUTY BTU/HR 0.0
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.00010000

*** RESULTS ***
<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outlet Temperature</td>
<td>69.795°F</td>
</tr>
<tr>
<td>Outlet Pressure</td>
<td>128.00 PSIA</td>
</tr>
<tr>
<td>Vapour Fraction</td>
<td>0.90229E-01</td>
</tr>
</tbody>
</table>

V-L Phase Equilibrium:

<table>
<thead>
<tr>
<th>COMP</th>
<th>F(I)</th>
<th>X(I)</th>
<th>Y(I)</th>
<th>K(I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

Appendix IV: Calculations

Pump Equations

Pump Unit

$S = \text{Size factor}; \ Q = \text{Flow rate in gallons / minute}; \ H = \text{Pump head in feet};$

$$S = Q(H)^{0.5}$$

$$S = 979.70(2929.32)^{0.5} = 53024.62$$

$C_B = \text{Bare module cost}$

$$C_B = \exp[9.7171 - 0.6019[\ln(S)] + 0.0519[\ln(S)]^2}$$

$$C_B = \exp[9.7171 - 0.6019[\ln(53024.62)] + 0.0519[\ln(53024.62)]^2} = \$11062$$

$C_P = \text{Purchase cost}; \ F_T = \text{Pump type factor} = 8.9; \ F_M = \text{Materials factor} = 1.35$

$$C_P = F_T F_M C_B$$

$$C_P = (8.9)(1.35)(11062) = \$132910$$

Electric Motor

$P_B = \text{Pump brake horsepower} = 551.6 \text{ hP};$

$$\eta_M = 0.80 + 0.0319[\ln(P_B)] + 0.00182[\ln(P_B)]^2$$

$$\eta_M = 0.80 + 0.0319[\ln(551.6)] + 0.00182[\ln(551.6)]^2 = 0.9288$$

$P_C = \text{Size parameter}; \ \eta_M = \text{Fractional motor efficiency};$

$$P_C = \frac{P_B}{\eta_M}$$

$$P_C = \frac{551.6}{0.9288} = 593.39 \text{ hP}$$

$C_B = \text{Bare module cost};$

$$C_B = \exp[5.8259 + 0.13141[\ln(P_C)] + 0.053255[\ln(P_C)]^2 + 0.028628[\ln(P_C)]^3$$

$$- 0.0035549[\ln(P_C)]^4}$$

$$C_B = \exp[5.8259 + 0.13141[\ln(593.39)] + 0.053255[\ln(593.39)]^2 + 0.028628[\ln(593.39)]^3$$

$$- 0.0035549[\ln(593.39)]^4} = \$32212$$

$C_P = \text{Purchase cost}; \ F_T = \text{Motor type factor} = 1;$

$$C_P = F_T C_B$$
Low-Grade Heat Recovery

\[ C_p = (1)(32212) = 32212 \]

**Total Pump Cost**

\[ C_{p-\text{Unit}} = \text{Purchase cost of unit} = 132910; \quad C_{p-\text{Motor}} = \text{Purchase cost of motor} = 32212; \quad C_{p-\text{Total}} = \text{Total cost}; \]

\[ C_{p-\text{Total}} = C_{p-\text{Unit}} + C_{p-\text{Motor}} \]

\[ C_{p-\text{Total}} = 132910 + 32212 = 165123 \]
Plate and Fin Heat Exchanger

\[ C_B = \text{Bare module cost}; \ A = \text{Surface area}; \]

\[ C_B = 2500A^{0.4} \]

\[ C_B = 2500(86833)^{0.4} \approx 236273 \]

\[ C_P = \text{Purchase cost}; \ F_B = \text{Bare module factor 2.17}; \text{With the addition of 2 units without additional installation cost}; \]

\[ C_P = F_B C_B \]

\[ C_P = (2.17)(236273) + 2(236273) = 985258 \]
Low-Grade Heat Recovery

**Liquid Expander**

Liquid Expander - 124

\[ C_B = 1400P^{0.70} \]
\[ C_B = 1400(1540)^{0.70} = 238447 \]

\[ C_P = F_B C_B \]
\[ C_P = (1.5)(238447) = 357671 \]

Liquid Expander - 336

\[ C_B = 1400P^{0.70} \]
\[ C_B = 1400(172)^{0.70} = 51371 \]

\[ C_P = F_B C_B \]
\[ C_P = (1.5)(51371) = 77056 \]

**Vapor Expander**

\[ C_B = 530P^{0.81} \]
\[ C_B = 530(1241)^{0.81} = 169900 \]

\[ C_P = F_B C_B \]
\[ C_P = (2.34)(169900) = 397567 \]
**Flash Column**

**Flash Column – 339**

t_p = Thickness needed to withstand internal pressure; P_d = internal design pressure = 280; D_i = inside shell diameter in inches = 78 inches; S = maximum allowable stress of the shell material in psi = 15000; E = fractional weld efficiency = .85;

\[
 t_p = \frac{P_d D_i}{2SE - 1.2P_d}
\]

\[
 t_p = \frac{(280)(78)}{2(15000)(.85) - 1.2(280)} = 0.45\ inches
\]

Doing similar calculations, the t_w, the thickness to withstand an earthquake or wind is 1.31 inches. The total thickness, t_v, is 0.88 inches. The shell thickness is 1 inch.

W = Weight of the shell; L is the vessel height; t_s = Shell thickness; \( \rho \) = Density of carbon steel;

\[
 W = \pi(D_i + t_s)(L + 0.8D_i)t_s \rho
\]

W = 28067 lbs

C_V = Vessel cost;

\[
 C_V = \exp[7.2756 - 0.81255\ln(W)] + 0.02297[\ln(W)]^2
\]

C_V = $104300

C_P = Purchase cost; F_B = Bare module factor = 4.16;

\[
 C_P = F_B C_B
\]

C_P = $477275

**Flash Column – 326**

Flash Column 326 can be calculated similarly with a resulting C_P of $1443377.
Condenser (Shell & Tube Heat Exchanger)

\( N_p = 6 \) passes

*Shell Side Properties*: \( C_p = 0.52 \) Btu/lb-°F; \( \mu = 0.0098 \) cP; \( k = 0.2219 \) Btu/hr-ft-°F; Sp. Gr = 0.597;

*Tube Side Properties*: \( C_p = 1.00 \) Btu/lb-°F; \( \mu = 0.67 \) cP; \( k = 0.363 \) Btu/hr-ft-°F; Sp. Gr = 1.00;

\( U = 100 \) Btu/sqft-hr-°F; Tube Side Velocity =5 ft/s

16 BWG tubing = Outer diameter = 0.75 inches; Inner Diameter = 0.62 inches

Square Pitch = 1 inch

\( T_{in} = 119 \) °F; \( T_{out} = 70 \)°F; \( T_{cw,in} = 65 \)°F; \( T_{cw,out} = 68 \)°F

*Mass flow of Ammonia* = 106751 lb/hr

\[
Q = \frac{(m)(C_p)(T_{out} - T_{in})}{(106751 \text{ lb/hr})(0.52 \text{ Btu/lb-°F})(119 \text{ °F - 70°F})} = 2.72 \times 10^6 \text{ Btu/hr}
\]

*Mass flow of Cooling Water* = \( \frac{Q}{(C_p)(T_{cw,in} - T_{cw,out})} \)

\[
(\frac{2.72 \times 10^6 \text{ Btu/hr}}{(100 \text{ Btu/sqft-hr-°F})(68^\circ F - 65^\circ F)}) = 906671.8 \text{ lb/hr}
\]

\[
\Delta T_{lm} = \frac{(T_{in} - T_{cw,out}) - (T_{out} - T_{cw,in})}{\ln((T_{in} - T_{cw,out})/(T_{out} - T_{cw,in}))} = 19.81^\circ F
\]

\[
R = \frac{(T_{in} - T_{out})}{(T_{cw,in} - T_{cw,out})} = 16.333
\]

\[
S = \frac{(T_{cw,out} - T_{cw,in})}{(T_{in} - T_{cw,in})} = 0.0555
\]

\( F_T = 0.912 \) (Seider)

\[
A = \frac{Q}{(U * F_T * \Delta T_{lm})} = 2.72 \text{ E06 Btu/hr}/(100 \text{ Btu-sqft-hr-°F} * 0.912 * 19.81^\circ F) = 1505.92 \text{ sqft}
\]

\[
A_{ci} = (m_c/V_t) = (906671.8 \text{ lb/hr} * 1 \text{cuft/62.4 lb})/(5 \text{ ft/s} * 3600 \text{s/hr}) = 0.80722 \text{ sqft/pass}
\]

\[
A_{in/tube} = \pi * D_{in}^2/4 = \pi * (0.62 \text{ inches})^2/4 = 0.3019 \text{ sqin/tube}
\]

\[
N_t = A_{ci}/(A_{in/tube}) = (0.80722 \text{ sqft/pass})/(0.3019 \text{ sqin/tube}) *(144 \text{sqin/1sqft}) = 385.02 \text{ tubes} = 385 \text{ tubes}
\]

\[
A_t = \frac{A}{(N_p * N_t)} = 1505.92 \text{ sqft} / (6 \text{ passes} * 385 \text{ tubes}) = 0.65188 \text{ sqft/tube}
\]

Length= \( A_t/(\pi * D_{in}) = 0.652 \) sqft/tube/((\pi*0.62in)*12) = 4.01 ft

*Recommendation: Use 4 ft tubes if available, otherwise 6 ft or 8 ft tubes work as well.*

\[
N_{Re} = \frac{D_p V_t/\mu_{in}}{(0.62 \text{ in}/12 \text{ in}/ft) * (62.4 \text{ lb/cuft}) * 5 \text{ ft/s}}/(0.67 cP x 1 \text{lb-ft-s/1488 cP}) = 35800
\]

\[
N_p = C_p * \mu_{in}/k_c = 1 \text{ Btu/lb-°F} * (0.67/1488 \text{ lb/ft-s}) * 3600 \text{ s/hr}/(0.363 \text{ Btu/ft-hr-°F}) = 4.465
\]

\[
Nu = 0.023 N_{Re}^{0.8} N_p^{0.4} = 183.98
\]

\[
h_{in} = k_{in} Nu/D_t = 0.363 \text{ Btu/ft-hr-°F} * (12 \text{in/ft}) * 184.1 = 1292 \text{ Btu/sqft-hr-°F}
\]
Low-Grade Heat Recovery

\[ 1/U = 1/h_o\left(D/D_o\right) + 1/h_i \]

\[ 1/h_o = \frac{1}{100-1/1290} \times (0.75 \text{ in}/0.62 \text{ in}) = 0.0112 \]

\[ h_o = 89.6 \text{ Btu/hr-sqft}^\circ\text{F} \]
Appendix V: MSDS Safety Data

MATERIAL SAFETY DATA SHEET

PRODUCT NAME: AMMONIA

1. Chemical Product and Company Identification

BOC Gases,
Division of
The BOC Group, Inc.
575 Mountain Avenue
Murray Hill, NJ 07974

BOC Gases
Division of
BOC Canada Limited
5975 Falbourne Street, Unit 2
Mississauga, Ontario L5R 3W6

TELEPHONE NUMBER: (908) 464-8100
24-HOUR EMERGENCY TELEPHONE NUMBER: (800) 424-9300
CHEMTREC (800) 424-9300

TELEPHONE NUMBER: (905) 501-1700
24-HOUR EMERGENCY TELEPHONE NUMBER: (905) 501-0802
EMERGENCY RESPONSE PLAN NO: 20101
2. Composition, Information on Ingredients

<table>
<thead>
<tr>
<th>INGREDIENT</th>
<th>% VOLUME</th>
<th>PEL-OSHA¹</th>
<th>TLV-ACGIH²</th>
<th>LD₅₀ or LC₅₀ Route/Species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>100.0</td>
<td>50 ppm TWA</td>
<td>25 ppm TWA</td>
<td>LC₅₀ 2000 ppm/4H</td>
</tr>
<tr>
<td>FORMULA: NH₃</td>
<td></td>
<td></td>
<td>35 ppm STEL</td>
<td></td>
</tr>
<tr>
<td>CAS: 7664-41-7</td>
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<tr>
<td>RTECS #: BO0875000</td>
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<td></td>
</tr>
</tbody>
</table>

¹ As stated in 29 CFR 1910, Subpart Z (revised July 1, 1993)
² As stated in the ACGIH 1994-95 Threshold Limit Values for Chemical Substances and Physical Agents

3. Hazards Identification

**EMERGENCY OVERVIEW**

Irritating or corrosive to exposed tissues. Inhalation of vapors may result in pulmonary edema and chemical pneumonitis. Slightly flammable.

**PRODUCT NAME:** AMMONIA

**ROUTE OF ENTRY:**

<table>
<thead>
<tr>
<th>Skin Contact</th>
<th>Skin Absorption</th>
<th>Eye Contact</th>
<th>Inhalation</th>
<th>Ingestion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

**HEALTH EFFECTS:**

Exposure Limits | Irritant | Sensitization |
----------------|---------|---------------|
Yes             | Yes     | No            |

Teratogen | Reproductive Hazard | Mutagen |
---|---|---|
No | No | Yes |

Synergistic Effects
None Reported

Carcinogenicity: -- NTP: No IARC: No OSHA: No

**EYE EFFECTS:**

Mild concentrations of product will cause conjunctivitis. Contact with higher concentrations of product will cause swelling of the eyes and lesions with a possible loss of vision.
SKIN EFFECTS:
Mild concentrations of product will cause dermatitis or conjunctivitis. Contact with higher concentrations of product will cause caustic-like dermal burns and inflammation. Toxic level exposure may cause skin lesions resulting in early necrosis and scarring.

INGESTION EFFECTS:
Since product is a gas at room temperature, ingestion is unlikely.

INHALATION EFFECTS:
Corrosive and irritating to the upper respiratory system and all mucous type tissue. Depending on the concentration inhaled, it may cause burning sensations, coughing, wheezing, shortness of breath, headache, nausea, with eventual collapse.

Inhalation of excessive amounts affects the upper airway (larynx and bronchi) by causing caustic-like burning resulting in edema and chemical pneumonitis. If it enters the deep lung, pulmonary edema will result. Pulmonary edema and chemical pneumonitis are potentially fatal conditions.

<table>
<thead>
<tr>
<th>NFPA HAZARD CODES</th>
<th>HMIS HAZARD CODES</th>
<th>RATINGS SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Health: 3</td>
<td>Health: 3</td>
<td>0 = No Hazard</td>
</tr>
<tr>
<td>Flammability: 1</td>
<td>Flammability: 1</td>
<td>1 = Slight Hazard</td>
</tr>
<tr>
<td>Reactivity: 0</td>
<td>Reactivity: 0</td>
<td>2 = Moderate Hazard</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 = Serious Hazard</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 = Severe Hazard</td>
</tr>
</tbody>
</table>
4. First Aid Measures

EYES:
Flush contaminated eye(s) with copious quantities of water. Part eyelids to assure complete flushing. Continue for a minimum of 15 minutes. PERSONS WITH POTENTIAL EXPOSURE TO AMMONIA SHOULD NOT WEAR CONTACT LENSES.

SKIN:
Remove contaminated clothing as rapidly as possible. Flush affected area with copious quantities of water. In cases of frostbite or cryogenic "burns" flush area with lukewarm water. DO NOT USE HOT WATER. A physician should see the patient promptly if the cryogenic "burn" has resulted in blistering of the dermal surface or deep tissue freezing.

INGESTION:
Not specified. Seek immediate medical attention.

INHALATION
PROMPT MEDICAL ATTENTION IS MANDATORY IN ALL CASES OF OVEREXPOSURE. RESCUE PERSONNEL SHOULD BE EQUIPPED WITH SELF-CONTAINED BREATHING APPARATUS. Conscious persons should be assisted to an uncontaminated area and inhale fresh air. Quick removal from the contaminated area is most important. Unconscious persons should be moved to an uncontaminated area, given mouth-to-mouth resuscitation and supplemental oxygen. Keep victim warm and quiet. Assure that mucus or vomited material does not obstruct the airway by positional drainage.

5. Fire Fighting Measures

<table>
<thead>
<tr>
<th>Conditions of Flammability: Nonflammable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash point: None</td>
</tr>
<tr>
<td>Method: Not Applicable</td>
</tr>
<tr>
<td>Autoignition: Temperature: 1274 °F (690 °C)</td>
</tr>
<tr>
<td>LEL(%): 16</td>
</tr>
<tr>
<td>UEL(%): 25</td>
</tr>
<tr>
<td>Hazardous combustion products: None</td>
</tr>
<tr>
<td>Sensitivity to mechanical shock: None</td>
</tr>
<tr>
<td>Sensitivity to static discharge: None</td>
</tr>
</tbody>
</table>

FIRE AND EXPLOSION HAZARDS:
The minimum ignition energy for ammonia is very high. It is approximately 500 times greater than the energy required for igniting hydrocarbons and 1000 to 10,000 times greater than that required for hydrogen.

EXTINGUISHING MEDIA:
Water fog. Use media suitable for surrounding fire.

FIRE FIGHTING INSTRUCTIONS:
If possible, stop the flow of gas. Since ammonia is soluble in water, it is the best extinguishing media—not only in extinguishing the fire, but also absorbing the escaped ammonia gas. Use water spray to cool surrounding containers.
6. Accidental Release Measures

Evacuate all personnel from affected area. Use appropriate protective equipment. If leak is in user's equipment, be certain to purge piping with inert gas prior to attempting repairs. If leak is in container or container valve, contact the appropriate emergency telephone number listed in Section 1 or call your closest BOC location.

7. Handling and Storage

Electrical Classification:
Class 1, Group D.

Earth-ground and bond all lines and equipment associated with the ammonia system. Electrical equipment should be non-sparking or explosion proof.

Gaseous or liquid anhydrous ammonia corrodes certain metals at ambient temperatures. The presence of oxygen enhances the corrosion of ordinary or semi-alloy steels. The addition of water inhibits this enhancement. Keep anhydrous ammonia systems scrupulously dry.

Use only in well-ventilated areas. Valve protection caps must remain in place unless container is secured with valve outlet piped to use point. Do not drag, slide or roll cylinders. Use a suitable hand truck for cylinder movement. Use a pressure regulator when connecting cylinder to lower pressure (<500 psig) piping or systems. Do not heat cylinder by any means to increase the discharge rate of product from the cylinder. Use a check valve to trap in the discharge line to prevent hazardous back flow into the cylinder.

Protect cylinders from physical damage. Store in cool, dry, well-ventilated area away from heavily trafficked areas and emergency exits. Do not allow the temperature where cylinders are stored to exceed 125°F (52°C). Cylinders should be stored upright and firmly secured to prevent falling or being knocked over. Full and empty cylinders should be segregated. Use a "first in-first out" inventory system to prevent full cylinders from being stored for excessive periods of time.

For additional handling recommendations, consult Compressed Gas Association Pamphlets P-1 and G2.

Never carry a compressed gas cylinder or a container of a gas in cryogenic liquid form in an enclosed space such as a car trunk, van or station wagon. A leak can result in a fire, explosion, asphyxiation or a toxic exposure.

8. Exposure Controls, Personal Protection

EXPOSURE LIMITS:\n
<table>
<thead>
<tr>
<th>INGREDIENT</th>
<th>% VOLUME</th>
<th>PEL-OSHA(^2)</th>
<th>TLV-ACGIH(^3)</th>
<th>LD(<em>{50}) or LC(</em>{50}) Route/Species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>100.0</td>
<td>50 ppm TWA</td>
<td>25 ppm TWA</td>
<td>LC(_{50}) 2000 ppm/4H</td>
</tr>
</tbody>
</table>

\(^{1}\) Refer to individual state of provincial regulations, as applicable, for limits which may be more stringent than those listed here.

\(^{2}\) As stated in 29 CFR 1910, Subpart Z (revised July 1, 1993)

\(^{3}\) As stated in the ACGIH 1994-1995 Threshold Limit Values for Chemical Substances and Physical Agents.

ENGINEERING CONTROLS:
Use local exhaust ventilation to reduce concentrations to within current exposure limits. A laboratory type hood is suitable for handling small or limited quantities.
PRODUCT NAME: AMMONIA

EYE/FACE PROTECTION:
Gas tight chemical goggles or full-face piece respirator.

SKIN PROTECTION:
Protective gloves made of any suitable material.

RESPIRATORY PROTECTION:
Level C respiratory protection with full face piece or self-contained breathing apparatus should be available for emergency use. Air purifying respirators must be equipped with suitable cartridges. Do not exceed maximum use concentrations. Do not use air purifying respirators in an oxygen deficient/immediately dangerous to life and health (IDLH) atmosphere. Consult manufacturers instructions before use.

OTHER/GENERAL PROTECTION:
Safety shoes, safety shower, eyewash "fountain".

9. Physical and Chemical Properties

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical state (gas, liquid, solid)</td>
<td>Gas</td>
<td></td>
</tr>
<tr>
<td>Vapor pressure at 70°F</td>
<td>94</td>
<td>psia</td>
</tr>
<tr>
<td>Vapor density at 60°F (Air = 1)</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>Evaporation point</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boiling point</td>
<td>-28</td>
<td>°F</td>
</tr>
<tr>
<td></td>
<td>-33.3</td>
<td>°C</td>
</tr>
<tr>
<td>Freezing point</td>
<td>107.9</td>
<td>°F</td>
</tr>
<tr>
<td></td>
<td>-77.7</td>
<td>°C</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific gravity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil/water partition coefficient</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solubility (H2O)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Odor threshold</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Odor and appearance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific gravity</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Odor threshold</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Odor and appearance</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A colorless gas with a pungent odor.

10. Stability and Reactivity

STABILITY:
Unstable

CONDITIONS TO AVOID (STABILITY):
None

INCOMPATIBLE MATERIALS:
Reacts vigorously with fluorine, chlorine, HCl, HBr, nitrosyl chloride, chromyl chloride, nitrogen dioxide, trioxoxygen difluoride, and nitrogen trichloride.
PRODUCT NAME: AMMONIA

HAZARDOUS DECOMPOSITION PRODUCTS:
Hydrogen at very high temperatures: 1544°F (840°C).

CONDITIONS TO AVOID (POLYMERIZATION):
None

HAZARDOUS POLYMERIZATION:
Will not occur.

11. Toxicological Information

MUTAGENIC:
Genetic mutations observed in bacterial and mammalian test systems.

OTHER:
Toxic effects to the respiratory system, senses, liver, kidneys and bladder observed in mammalian species from prolonged inhalation exposures at above 100 ppm.

12. Ecological Information

OTHER ENVIRONMENTAL INFORMATION:
The reportable quantity is the minimum quantity of a material that when released, requires reporting to the appropriate Federal, State and local officials. Notification requirements are found under CERCLA Section 103(a). Initial notification may be by telephone, radio, or in person. A written follow-up notice is also required.

13. Disposal Considerations

Do not attempt to dispose of residual waste or unused quantities. Return in the shipping container PROPERLY LABELED, WITH ANY VALVE OUTLET PLUGS OR CAPS SECURED AND VALVE PROTECTION CAP IN PLACE to BOC Gases or authorized distributor for proper disposal.

14. Transport Information

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>United States DOT</th>
<th>Canada TDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROPER SHIPPING NAME:</td>
<td>Ammonia, Anhydrous, liquefied</td>
<td>Ammonia, Anhydrous, liquefied</td>
</tr>
<tr>
<td>HAZARD CLASS:</td>
<td>2.2</td>
<td>2.4 (9.2)</td>
</tr>
<tr>
<td>IDENTIFICATION NUMBER:</td>
<td>UN 1005</td>
<td>UN 1005</td>
</tr>
<tr>
<td>SHIPPING LABEL:</td>
<td>NONFLAMMABLE GAS</td>
<td>CORROSIVE GAS</td>
</tr>
</tbody>
</table>

Additional Marking Requirement: “Inhalation Hazard”
If net weight of product \( \geq 100 \) pounds, the container must be also marked with the letters “RQ”.

Additional Shipping Paper Description Requirement: “Poison Inhalation Hazard, Zone A”
If net weight of product \( \geq 100 \) pounds, the shipping papers must be also marked with the letters “RQ”.

15. Regulatory Information

Ammonia is listed under the accident prevention provisions of section 112(r) of the Clean Air Act (CAA) with a threshold quantity (TQ) of 10,000 pounds.
PRODUCT NAME: AMMONIA

SARA TITLE III NOTIFICATIONS AND INFORMATION
Ammonia is listed as an extremely hazardous substance (EHS) subject to state and local reporting under Section 304 of SARA Title III (EPCRA) with a reportable quantity (RQ) of 100 pounds.

The presence of Ammonia in quantities in excess of the threshold planning quantity (TPQ) of 500 pounds requires certain emergency planning activities to be conducted.

SARA TITLE III - HAZARD CLASSES:
Acute Health Hazard
Sudden Release of Pressure Hazard
Reactivity Hazard

SARA TITLE III - SECTION 313 SUPPLIER NOTIFICATION:
This product contains the following toxic chemicals subject to the reporting requirements of section 313 of the Emergency Planning and Community Right-To-Know Act (EPCRA) of 1986 and of 40 CFR 372:

<table>
<thead>
<tr>
<th>CAS NUMBER</th>
<th>INGREDIENT NAME</th>
<th>PERCENT BY VOLUME</th>
</tr>
</thead>
<tbody>
<tr>
<td>7664-41-7</td>
<td>AMMONIA</td>
<td>100.0</td>
</tr>
</tbody>
</table>

This information must be included on all MSDS that are copied and distributed for this material.

16. Other Information

Compressed gas cylinders shall not be refilled without the express written permission of the owner. Shipment of a compressed gas cylinder which has not been filled by the owner or with his/her (written) consent is a violation of transportation regulations.

DISCLAIMER OF EXPRESSED AND IMPLIED WARRANTIES:
Although reasonable care has been taken in the preparation of this document, we extend no warranties and make no representations as to the accuracy or completeness of the information contained herein, and assume no responsibility regarding the suitability of this information for the user's intended purposes or for the consequences of its use. Each individual should make a determination as to the suitability of the information for their particular purpose(s).
SAFETY DATA SHEET

1 Identification of the substance or preparation and of the company/undertaking

Product Name: R-245fa
Datasheet Number: 736355 2.0.0
Use of the substance/preparation: Blowing agent
Product Part Number: 736355 (50 kg)
Name of Supplier: Wilhelmsen Maritime Services AS
Address of Supplier: Willem Barentszstraat 50
3165 AB Rotterdam-Albrandswaard, The Netherlands
Telephone: +31 10 4877 777
Fax: +31 10 4877 888
Responsible Person: Leen de Visser, Product HSE Manager, Tel.: +31 6 538 63736
Email: Leen.de.Visser@Wilhelmsen.com
Name of Manufacturer: Wilhelmsen Maritime Services AS, Business Unit Refrigeration
Address of Manufacturer: Strandveien 20
P.O.Box 33
NO-1324 LYSAKER
Norway
Telephone: +47 67 584550
Emergency Telephone: NCEC: +44 1865 407333, CHEMTREC (800) 424 9300
American Chemistry Council +1 703 527 3887, Greece +30 210 7793777

2 Composition/information on ingredients

<table>
<thead>
<tr>
<th>Chemical Name</th>
<th>Concentration</th>
<th>CAS Number</th>
<th>EC Number</th>
<th>R Phrases</th>
<th>Symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,1,1,3,3- Pentafluoropropane (R-245 fa)</td>
<td>100</td>
<td>460-73-1</td>
<td>419-170-6</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

3 Hazards identification

- Odour: Sweet ether-like odour
- Appearance: Liquid, colourless, volatile
- Contact with eyes: May cause irritation
- Contact with skin: Repeated exposure may cause skin dryness or cracking (R66)
- Inhalation: May cause dizziness, confusion, headache or stupor, In cases of severe exposure, anaesthesia may develop
- Ingestion: Not regarded as a potential route of exposure.

4 First aid measures

Contact with skin
- Remove contaminated clothing immediately and drench affected skin with plenty of water. Then wash with soap and water
- Contaminated clothing should be laundered before reuse

Contact with eyes
- Irrigate eyes thoroughly whilst lifting eyelids
- Obtain immediate medical attention

Ingestion
- Not regarded as a potential route of exposure.
- Give 200-300mls (half pint) water to drink
- Seek immediate medical attention

Inhalation
- Remove patient to fresh air
- Apply artificial respiration only if patient is not breathing
- Seek immediate medical attention

General
- In case of accident or if you feel unwell, seek medical advice immediately (show the label where possible) (S45)

Notes to Physicians
4 First aid measures (...)
Do not give andrenalin or equivalent medicines.
Do not give stimulants.

5 Fire-fighting measures
- Unstable above 250 deg C, Auto-ignition point >700 deg C at 760 mm Hg
- Non-flammable
- Decomposition products may include halogen compounds
- Portable containers should be moved if possible and without risk
- Keep container(s) exposed to fire cool, by spraying with water
- Smoke from fires is corrosive. Take precautions to protect personnel from exposure
- Use water spray or fog to knock down and absorb corrosive fumes
- Inform Fire Brigade of potential danger of exploding and rocketing cylinders

6 Accidental release measures
Personal Precautions
- Wear protective clothing as per section 8
- Shut off all ignition sources
- Shut off source of leak if safe to do so
- In poorly ventilated areas or confined spaces, use an airline respirator or self-contained breathing apparatus

Environmental Precautions
- Avoid release to the environment. Refer to special instructions/Safety data sheets (S61)

Clean Up Actions
- Shut off source of leak if safe to do so
- Allow product to evaporate
- Ventilate area

7 Handling and storage
Handling
- Use only in well ventilated areas (S51)
- Restricted to professional users
- Do not smoke
- Do not breathe vapour (S23)
- Avoid contact with skin and eyes (S24/25)
- Eyewash bottles should be available

Storage
- Keep in a cool, dry, well ventilated place
- Keep container tightly closed and at a temperature not exceeding 50 °C (S7/47)

Specific use(s)
- If container temperature exceeds boiling point, cool the container before opening.
- R-245fa should not be mixed with air above atmospheric pressure for leak testing or any other purpose. Use dry nitrogen to leak test equipment pressurized with R-245fa.

8 Exposure controls and personal protection
Exposure Limits
- TLV (TWA) 300ppm (1,1,1,3,3-Pentafluoropropane)

Exposure controls
- The undiluted product must not be used in a confined space without good ventilation
- Engineering controls should be provided which maintain airborne concentrations as low as practicable

Occupational exposure controls
- In poorly ventilated areas or confined spaces, use an airline respirator or self-contained breathing apparatus
- Wear suitable protective clothing, including eye/face protection and gloves (neoprene or nitrile are recommended)
- Wear safety boots when handling cylinders.

Boots
Gloves
Suit
Goggles
8 Exposure controls and personal protection (....)

9 Physical and chemical properties
- Odour: Sweet ether-like odour
- Appearance: Liquid, colourless, volatile
- pH - not applicable
- Boiling point 15 °C at 760 mm/Hg
- Vapour pressure 17.8 psia at 20 deg C
- Vapour density (air = 1) 4.6
- Freezing point <-153 °F at 1 atmospheres
- Melting point - not known
- Water solubility 7.18 g/l
- Specific gravity (water=1) 1.32
- Non-flammable
- Unstable above 250 deg C, Auto-ignition point >700 deg C at 760 mm Hg
- Log Pow 1.35 @ 21.5 °C

10 Stability and reactivity
- This article is considered stable under normal conditions
- Avoid overheating, Keep away from naked flames, incandescent or hot surfaces
- Avoid contact with magnesium and alloys containing more than 2% magnesium.
- Keep away from open flames, hot surfaces and sources of ignition.

11 Toxicological information
Toxicological information
- LC50 (inhalation, rat) >200,000 mg/l/4h
- LD50 (dermal) : >2000 mg/kg

Inhalation
- In cases of severe exposure, anaesthesia may develop
- May disturb the respiration, heart and nervous system

Contact with skin
- Not hazardous

Contact with eyes
- May cause irritation

Ingestion
- Not regarded as a potential route of exposure.

Carcinogenicity
- No evidence of carcinogenic effects

12 Ecological information
Ecotoxicity
- EC50 (Daphnia magna) 97.9 mg/l (48 hr)
- LC50 (rainbow trout) 81.8 mg/l (96 hr)

Mobility
- Water solubility 7.18 g/l

Persistence and Biodegradability
- No information available

Bioaccumulation Potential
- Bioaccumulation is insignificant

Other Adverse Effects
- Global Warming Potential: 950 (CO2 = 1; 100 years)
- Ozone Depletion Potential: 0.000
- GWP and ODP values according to IPCC/ASHRAE/ARI.
- IPCC = Intergovernmental Panel on Climate Control
- ASHRAE = American Society of Heating, Refrigeration and Air-Conditioning Engineers
- ARI = American Refrigeration Institute
13 Disposal considerations
Classification
- This material and/or its container must be disposed of as hazardous waste
Disposal considerations
- Do not discharge into drains or the environment, dispose to an authorised waste collection point
- Disposal should be in accordance with local, state or national legislation

14 Transport information
- Not classified as hazardous for transport

15 Regulatory information
Classification and labelling
- Not classified as hazardous for supply
Risk Phrases
- Not applicable
Safety Phrases
- Not applicable

16 Other information

The information provided about the product on this Safety Data Sheet has been compiled from knowledge of the individual constituents. The data given here is based on current knowledge and experience. This Safety Data Sheet describes the product in terms of safety requirements and does not signify any warranty with regard to the product’s properties. The data given here only applies when product used for proper application(s). The product is not sold as suitable for other applications - usage in such may cause risks not mentioned in this sheet. Do not use for other application(s) without seeking advice from manufacturer.

This Safety Data Sheet is provided in compliance with The Dangerous Substances Directive (67/548/EEC)
This Safety Data Sheet is provided in compliance with The Dangerous Preparations Directive (88/379/EEC)
This Safety Data Sheet is provided in compliance with The Safety Data Sheets Directive (2001/58EC)